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RELATION OF ORE DEPOSITS TO DIFFERENT TYPES OF INTRUSIVE BODIES IN UTAH.[1]

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INTRODUCTION.

The ore deposits of Utah are for the most part associated with igneous rocks and present especially favorable opportunity for observations on the relations of ore deposition to different types of intrusive rock bodies. This is due in no small part to block faulting since intrusion that has brought into the field of observation bodies intruded at greatly differing depths, such faulting for example as that along the Wasatch front and along the west side of the Mineral Range. The relatively small size of all of the intrusive bodies as compared with those to the west in California and to the north in Idaho and Montana, seems also favorable to the study of the problem.

Associated with certain of the intrusive bodies are metal deposits of great economic importance, while associated with other bodies the deposits are small, and their chief commercial importance lies in the fact that much money and effort have been spent in fruitless prospecting for paying mines.

The intrusive bodies may be divided into two types, namely: lac-

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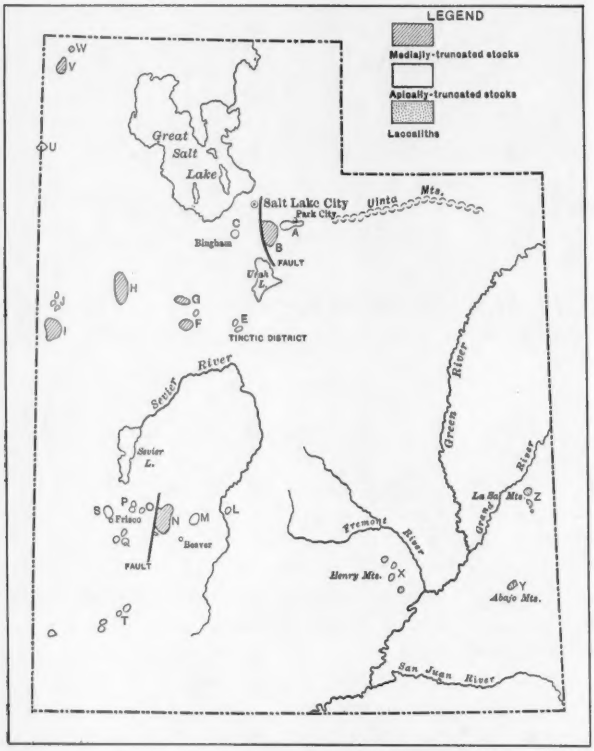

FIG. 16. Map showing the location of the principal intrusive bodies of Utah. *A*, Clayton Peak and Park City stocks; *B*, Little Cottonwood stock; *C*, Oquirrh Range stock; *E*, Tintic stock; *F*, Desert Mountain stock; *G*, Sheep Rock stock; *H*, Granite Mountain stock; *I*, Ibapah stock; *J*, Clifton stocks; *L*, Antelope stock; *M*, Tushar stock; *N*, Mineral Range stock; *O*, Granite Range stock; *P*, Beaver Lake stock; *Q*, Star Range stock; *S*, San Francisco stock; *T*, Iron Springs stocks; *U*, Ombe Range stock; *V*, Grouse Range stock; *W*, Raft River stock; *X*, Henry Mountain laccoliths; *Y*, Abajo Mountain laccoliths; *Z*, La Sal Mountain laccoliths.

coliths and stocks. The latter show different characteristics dependent on the distance below the top to which they have been eroded and on this basis may, for convenience in description, be designated as apically-truncated stocks and medially-truncated stocks. By apically-truncated stocks is meant those that are cut by the present erosion surface not far below the original top, while by medially-truncated stocks is meant those that are cut considerably farther below the original top. For still deeper portions the term basally-truncated stock might be employed.

The medially-truncated stocks probably comprise more than 75 per cent. in area of the exposed intrusive masses and are nearly equal in number to the other types. The apically-truncated stocks and laccolithic bodies are represented by several examples each, the former being both areally and numerically most important.

The accompanying sketch map (Fig. 16) shows the number and location of the different types of intrusive bodies of the state and in a general way the relative size of the different intrusive bodies in the western part of the state. The individual members of the laccolithic groups are too small to have their relative size even approximately shown on a map of the scale of the figure.

With this relative abundance of the types in mind, it is somewhat surprising to find that not a single mine of first- or even of second-class importance has been developed associated with either the medially-truncated stocks or the laccolithic bodies. Of the total metal output of the state, with a value of over $635,000,000[2] to the close of 1913, less than one-half of one per cent. has been derived from deposits associated with these two types; and of the recorded metal mining company dividends amounting to over $111,000,000, none is known to have been derived from deposits associated with either, though doubtless individual miners and prospectors, and perhaps companies, have produced and marketed ores at a profit from such deposits. It is certain that the commercial importance of both has been negative, that is, more has been expended in prospecting, mining, etc., than has been realized

[2] Heikes, V. C., U. S. Geol. Survey Mineral Resources, 1913, pt. 1, p. 366, 1914.

from the sale of ore.[3] Nearly every one of the apically truncated stocks has important ore bodies associated with it, and it is from this type that the great bulk of the metal output of the state has been derived. It may be mentioned that there has been important production from deposits not known to be directly associated with intrusive bodies, notably those of the Silver Reef district, while somewhat similar occurrences of ore are present in other districts.

It is with an attempt at a determination of the causes that have resulted in the varying importance of the deposits associated with the different intrusive bodies that this paper has to deal.

CHARACTER OF INTRUSIVE BODIES.

The larger intrusive bodies of the state as already noted may be included under two general types, namely laccoliths and stocks.

By laccolith, as here used, is meant an intrusive body that occupies space between the strata of earlier rocks formed mainly by the forcing apart of the strata. The characteristic feature of the laccolith, as compared with the stock, is that it has a floor and that it is connected with the deeper source of igneous material by a relatively small conduit.[4]

By a stock is meant a body that is essentially cross-cutting in its relation to strata and, as contrasted with a laccolith, has no bottom or floor and frequently increases downward in area of horizontal cross section, or at least has a relatively large connection with the deeper source from which its material was derived.

[3] The deposits in the western part of the Little Cottonwood district may possibly be regarded as associated with the Little Cottonwood stock rather than the Clayton Peak stock, in which case the above statement would have to be somewhat modified. It is a striking fact, however, that there is but little mineralization either in the Little Cottonwood stock or the associated pre-Cambrian rocks, while to the eastward, though locally influenced by structural features and the character of the rocks, there is an increase in mineralization through the early Paleozoic rocks of the Little Cottonwood district and a culmination in the great deposits in the late Paleozoic and early Mesozoic rocks of the Park City district.

[4] That a floor is an essential feature of the laccolith has recently been emphasized by Prof. A. C. Lawson, though this was plainly implied in the original definition of Gilbert.

There are, of course, gradations between stocks and laccoliths, and there may be offshoots from stocks that have the character of sheets or laccoliths. In Utah, however, the separation is rather marked. Laccoliths are the prevailing type in the sandy and shaly Mesozoic sediments of the southeastern part of the state, while stocks prevail in the Paleozoic limestones and quartzites of the western part. Associated with both types are, of course, dikes, sills, etc. Some of the western bodies that are here regarded as stocks have been designated as laccoliths by other writers.

Leith and Harder[5] regard the intrusive bodies of the Iron Springs district as laccoliths though, as their sections show, they increase in size downward, so far as exposed, and no floor has been revealed nor does the attitude of the adjacent sediments suggest a floor. The doming of the overlying formations is pronounced but this is little, if any, more characteristic of laccoliths than of stocks and cannot be regarded as critical evidence.

Likewise the authors of Professional Paper No. 38[6] apparently regard the larger intrusive bodies of the Bingham district as laccoliths, though as in the Iron Springs district so far as exposed they also increase in size downward and show no indication of an underlying floor.

This is in striking contrast to the conditions in southeastern Utah, where all workers recognized the presence of the floors even before Dr. Gilbert formulated the laccolithic hypothesis.

Laccoliths.—The laccolithic bodies occur in three groups in the southeastern part of the state, the La Sal, the Abajo, and the Henry Mountains. Each of these consists of numerous laccolithic bodies of varying size and shape intruded at different horizons in the Mesozoic sediments.

The physical character of the rocks constituting the bodies varies greatly with the size of the laccolith. Some of the small outlying laccoliths of the Henry Mountain group are almost glassy

[5] Leith, C. K., and Harder, E. C., "The Iron Ores of the Iron Springs District, Southern Utah," U. S. Geol. Survey Bull. 338, 1908.

[6] Boutwell, J. M., Keith, Arthur, and Emmons, S. F., "Economic Geology of the Bingham Mining District, Utah," U. S. Geol. Survey Prof. Paper 38, 1905.

in texture and have the general appearance of dense lava, for which indeed they have sometimes been mistaken. The rock of the larger bodies is moderately coarse-grained and in the largest there are a few dikes cutting the main intrusive rock.

Chemically, the laccolithic rocks are all of intermediate composition, namely quartz monzonite, granodiorite, or quartz diorite.

The following analyses are of two rocks that are believed to be representative of the La Sal and Henry Mountain bodies:

ANALYSES OF ROCKS FROM LACCOLITHIC BODIES.

	A.	B.
SiO_2	61.21	62.88
Al_2O_3	17.10	17.13
Fe_2O_3	2.72	1.86
FeO	1.88	2.58
MgO	1.47	1.48
CaO	4.83	5.39
Na_2O	5.66	4.50
K_2O	3.00	2.25
H_2O+	.34	.16
H_2O-	.68	.42

A. Monzonite porphyry. Two miles west of Mount Peale, La Sal Mountains. Collected by L. M. Prindle. Analysis by W. F. Hillebrand.

B. Granodiorite porphyry. Mount Hillers, Henry Mountains. Collected by G. K. Gilbert. Analysis by W. F. Hillebrand.

Stocks.—Intrusive stocks are confined to the western part of the state and further are largely restricted to two main east-west belts of igneous rocks that are associated with broad structural features.

One of these belts is in the northern part of the state, the other in the southern. As regards the main intrusive bodies the northern belt may be subdivided into (*a*) the zone containing the Park City-Little Cottonwood-Oquirrh Range stocks, and (*b*) the series of stocks extending westward from the Tintic district to those of the Deep Creek Range. The southern belt may be subdivided into (*a*) the east-west zone extending from the Tushar Range through through the Mineral Mountain to the Star and San Francisco ranges, and (*b*) the belt extending in a southwest direction through the Iron Springs region. In each of these belts asso-

ciated with the intrusive rocks are abundant extrusive rocks. The north-south faulting of the Basin ranges is in general transverse to these zones and has raised portions of them considerably above their normal position as related to other portions.

In addition to the above there are intrusive bodies in the Raft River, Grouse, and Ombe ranges in the northwestern part of the state.

Since stocks normally increase in size downward it is to be expected that a medially-truncated stock will be of greater areal extent, and such is the case. The medially-truncated Little Cottonwood stock is much larger than the apically-truncated stocks to the east in the Park City district or to the west in the Oquirrh Range. Likewise the medially-truncated Mineral Range stock is much larger than the apically-truncated stocks to the east and west. The same relation holds true in comparing the medially-truncated Ibapah stock and the apically-truncated Clifton stock of the Deep Creek Range. Of the other deeply eroded stocks the Granite Range, Grouse Range, Desert Range, and Sheep Rock stocks are all relatively large while the apically-truncated stocks of the Tintic and Iron Springs regions are relatively small. In physical character the medially-truncated stocks are typically of granitic texture while the apically truncated stocks range from granitic to porphyritic. In chemical composition the medially-truncated stocks are distinctly more siliceous, ranging from granodiorite to granite while apically-truncated stocks range from quartz monzonite to quartz diorite.

It has not been shown that the intrusive rocks of the state are all of the same age, but there can be little doubt that the stocks included in each of the "zones" or "belts" described below were intruded during the same period.

The general nature of the intrusive zones may perhaps be best understood by a brief description of certain ones.

The Park City-Little Cottonwood-Oquirrh Range zone consists of a large central mass, the Little Cottonwood stock, in contact with pre-Cambrian and early Paleozoic rocks. This has been brought into the field of observation by the great Wasatch fault. To the eastward of this central mass is the smaller Clayton Peak

stock intruded into Paleozoic rocks, and still farther to the east the stocks of the Park City area intruded into upper Paleozoic and Mesozoic rocks. To the westward across a broad desert valley are the Oquirrh Range stocks in upper Paleozoic rocks.

The Little Cottonwood stock, as noted, has been relatively raised by the great Wasatch fault and deeply dissected by erosion exposing pre-Cambrian rocks and is classed as a medially-truncated stock. The Park City and Oquirrh Range stocks have been much less deeply eroded and are regarded as apically-truncated stocks. All may be upward projections from a larger deeper seated mass, or what Prof. R. A. Daly has designated cupolas.

ANALYSES OF ROCKS FROM THE LITTLE COTTONWOOD, BINGHAM, AND PARK CITY STOCKS.

	1	2	3	4
SiO_2	67.02	63.46	59.35	58.64
Al_2O_3	15.78	15.93	16.36	15.35
Fe_2O_3	1.56	2.61	2.90	3.25
FeO	2.8	2.31	3.36	2.54
MgO	1.09	2.27	3.08	2.84
CaO	3.31	4.33	5.03	5.37
Na_2O	3.85	3.66	3.73	3.60
K_2O	3.67	3.49	3.85	4.23
H_2O-	.29	.27	.28	.86
H_2O	.63	.74	.64	1.50
TiO_2	.37	.62	.87	.83

1. Granodiorite. Little Cottonwood stock. R. C. Wells, analyst.
2. Quartz diorite. East side of Brighton Gap. W. F. Hillebrand, analyst. U. S. Geol. Survey Prof. Paper 78, p. 79.
3. Quartz diorite. Three-fourths of a mile northeast of Clayton Peak. W. F. Hillebrand, analyst. U. S. Geol. Survey Prof. Paper 78, p. 79.
4. Monzonite. British tunnel, Last Chance mine, Bingham District. E. F. Allen, analyst. U. S. Geol. Survey Prof. Paper 38, p. 178.

The rock of the medially-truncated Little Cottonwood stock is typically granitic in texture while those of apically-truncated stocks in the higher formations of the Park City and Bingham Cañon districts are typically porphyritic in texture. As is normal for the deeper eroded stocks the Little Cottonwood stock has a much larger surface exposure than those to the east and west.

In chemical composition the rocks of the deeper truncated body

are distinctly more siliceous than those of the shallower truncated bodies. The preceding table shows the composition of rocks of different stocks in this zone. They are all monzonitic in character grading toward diorite in one direction and granite in the other.

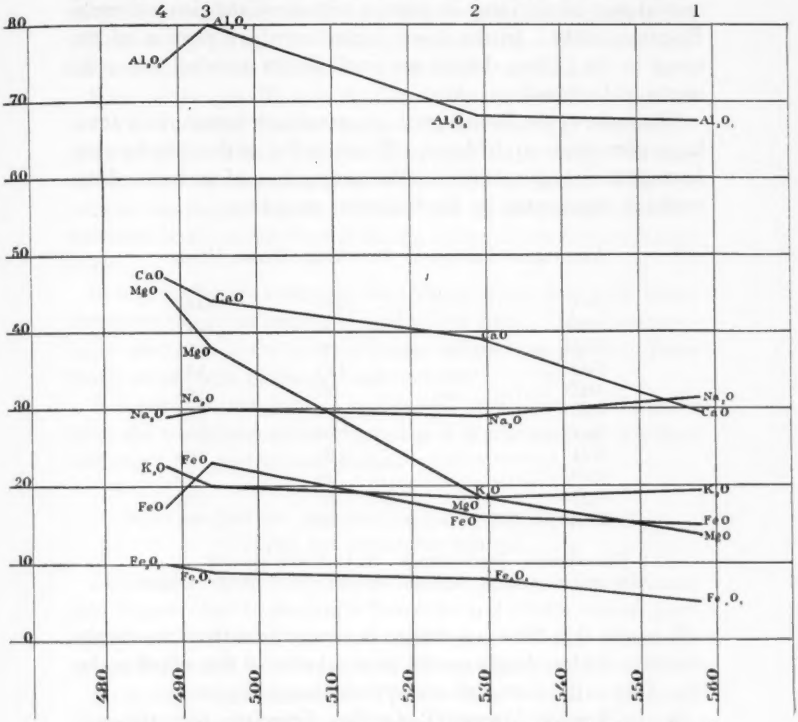

FIG. 17. Diagram showing change in the principal oxides in the stocks of the Park City-Little Cottonwood-Oquirrh Range zone. The molecular proportion of silica in each analysis is plotted as an abscissa, the remaining oxides being plotted on an ordinate located by the silica abscissa. Ratios multiplied by 500 for convenience in plotting.

In Fig. 17 the change in the principal oxides is graphically represented. It will be seen that there is a rather uniform change from

the central mass to the eastward and that a similar change is indicated to the westward, though the variation in the Bingham Canyon rock shows some change from those to the east.

In the Deep Creek Range the Ibapah stock is a large body in the central part of the range in contact with pre-Cambrian and early Paleozoic rocks. In the down faulted northern portion of the range in the Clifton district are small stocks intruded into sediments of Carboniferous age.

The rocks of the Ibapah stock are granitic in texture with some large phenocysts of feldspar. Those in the smaller stocks vary from granitic to porphyritic. The composition of the rocks of the stocks is represented by the following analyses:

ANALYSES OF ROCKS FROM DEEP CREEK RANGE, UTAH.

	1.	2.
SiO_2	70.67	62.84
Al_2O_3	16.24	14.21
Fe_2O_3	.37	.91
FeO	1.15	3.75
MgO	.26	3.04
CaO	1.71	4.72
Na_2O	3.95	2.85
K_2O	4.85	4.60
H_2O	.29	.26
H_2O —	.64	1.23
TiO_2	.23	.42

1. Granodiorite. Ibapah stock. R. C. Wells, analyst.
2. Quartz monzonite. Clifton District. R. C. Wells, analyst.

It is seen that there is a change in composition from the deeply eroded to the less deeply eroded stocks similar to that noted in the Park City-Little Cottonwood-Oquirrh Range region.

In the Tuschar-Mineral Range-San Francisco belt, the central Mineral Range stock is a large body in contact with Paleozoic and Mesozoic sediments raised to its present position by the Mineral Range fault. To the east the Tuschar stock is intruded into Tertiary volcanics and to the west the stocks are intruded into Tertiary volcanics and underlying Mesozoic and Paleozoic sediments. The Mineral Range stock is granitic in texture, while

those to the west and east vary from granitic to porphyritic, those in the volcanic rocks being distinctly porphyritic.

Chemical analyses are not available for comparison of these stocks, but field and microscopic study show that the large deeply eroded Mineral Range stock is distinctly granitic in composition while those to the east and west are monzonitic, a difference similar to that noted in the two belts previously mentioned.

Some of the apically-truncated stocks do not have a comparable medially-truncated type, as those of the Iron Springs district and possibly of the Tintic district, though the latter might be compared with the deeper truncated stocks to the west. Likewise some of the deeper truncated stocks have no comparable apically-truncated body, as the Granite Range stock and the Grouse Range stock.

In and associated with both the Granite Range and Raft River stocks are numerous pegmatitic and aplitic dikes. These are especially abundant in the Granite Range where they probably form nearly 20 per cent. of the exposed surface.

It is possible that detailed studies will reveal minor differences from the conditions stated above, but it is not believed that they will affect the general conclusions.

MINERALIZATION ASSOCIATED WITH THE DIFFERENT TYPES OF INTRUSIVE BODIES.

Laccoliths.—Mineralization in the laccoliths consists of small gold-copper veins in the larger laccoliths and a little contact mineralization in adjacent calcareous sediments. There is practically no mineralization associated with the smaller laccolithic bodies.

Medially-truncated Stocks.—There is little mineralization in the intrusive rocks of the deeper-truncated stocks. Pegmatitic gold-quartz veins are present in the Ibapah and Raft River stocks and extend into adjacent quartzites. Galena-fluorite veins are present in the Granite Range stock and small veins said to contain copper are reported in the Mineral Range stock, and similar veins are present in some of the other deeply eroded stocks.

In the adjacent sedimentary rocks contact deposits and replace-

ment veins are present, associated with practically all the stocks. Both are most abundant associated with the Mineral Range stock but nowhere have they been of large importance.

Apically-truncated Stocks.—Extensive fissure and replacement fissure deposits are present in the intrusive rock of practically all the apically-truncated stocks. Quartz-tourmaline-copper replacement veins are present in the San Francisco and Clifton stocks, and in the latter are tourmaline-scheelite pegmatitic veins or dikes; biotite-orthoclase-sericite-copper deposits in the Bingham Canyon stock; lead-silver zinc veins in the Bingham stock, and lead-silver and gold-copper veins in the Tintic stock. Few deposits have been worked in the Park City intrusives, though the lead-silver veins have been followed from the sedimentary rocks into the intrusive rock.

In the adjacent sedimentary rocks intense contact metamorphism has taken place near the San Francisco, Clifton, Little Cottonwood, and Iron Springs stocks, and less intense associated with the Bingham, Tintic and other stocks. Replacement veins are present in the rocks adjacent to all the stocks. These have yielded large amounts of lead, copper, silver and zinc, and to the present time have been the most productive type in the State. Associated with the stocks in the southern belt are deposits in the effusive rocks, that have yielded important amounts of lead, zinc, copper and precious metals.

Comparing the different types of intrusive bodies then, we find that the mineralization associated with the laccoliths is not extensive and is largely confined to the intrusive bodies, though there has been slight mineralization in the adjacent sedimentary rocks.

Mineralization associated with the medially-truncated stocks is comparatively slight and is present both in the intrusive bodies and in the adjacent rocks. That in the intrusive body is prevailingly of the deep-seated type, approaching pegmatite in character, as shown by the pegmatitic gold-quartz veins of the Ibapah and Raft River stocks.

Mineralization in the adjacent sedimentary rocks is most important in the Mineral Range, where limestone is present, and

this has doubtless influenced the extent of mineralization. (Most of the deeper-truncated stocks are in contact with the siliceous rocks of the early Cambrian and pre-Cambrian.) That the character of the enclosing rock has not been the determining factor in the mineralization is indicated by the fact that important deposits occur in siliceous sediments and effusive rocks associated with apically-truncated stocks, as in the Bingham, Park City, San Francisco, and other districts; while the deposits in the limestone of the Mineral Range are not comparable in importance with those of the Star and Park City districts which occur in sedimentary rocks of essentially the same age and character associated with apically-truncated stocks.

Associated with the apically-truncated stocks is extensive mineralization both in the intrusive rock and in the adjacent sedimentary and effusive rocks. The mineralization in the stocks is prevailingly of the high temperature type, including tourmaline veins, etc., as already noted, though the lead-silver veins of the Tintic and Bingham districts indicate formation at only moderate temperature and pressure. In the sedimentary and effusive rocks the deposits show more or less complete gradation from the high temperature contact type to fissure deposits formed at moderate and comparatively low temperature.

PROPOSED EXPLANATION OF THE CAUSES OF THE DIFFERENCE IN MINERALIZATION ASSOCIATED WITH THE DIFFERENT INTRUSIVE TYPES.

In the following paragraphs it is assumed that the ore deposits are genetically associated with the intrusive rocks and that the solutions that deposited the ores were derived in large part at least from differentiation of igneous material. The writer considers that the ore deposits of the state present ample evidence to support this belief, but it is not proposed to present the evidence in this place. Neither is it proposed to discuss in detail the evidence for and against different methods of introduction of the intrusive bodies. The writer presents what to him seems the most natural explanation of the observed facts as regards the upper

portion of the intrusive zone, which is the only portion open to observation in this area.

Laccoliths.—The material forming the laccolithic bodies entered the space occupied through a relatively narrow channel. As soon as the active flow through this passage into the laccolithic chamber ceased, the material in the passage quickly solidified, effectively sealing off the laccolith from the deeper source from which its material had been derived. If it chanced to be a small body approaching a sill or sheet in character, the solidification was rapid and there was little opportunity for differentiation. As

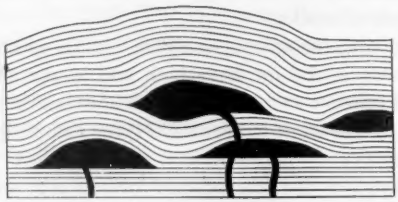

FIG. 18. Ideal cross-section of grouped laccoliths of Henry Mountains. After G. K. Gilbert.

already noted some of the smaller laccolithic bodies have almost the texture of lava and in such cases there was evidently little more opportunity for differentiation than in a surface flow. Associated with such bodies there is practically no mineralization either in the igneous masses or in the adjacent sedimentary rocks. In the larger laccoliths, solidification proceeded more slowly. The resultant rocks are much more coarsely crystalline and in some cases, as already noted, a few dikes are present in the laccoliths. The presence of the dikes may be interpreted as indicating that the crystallization was sufficiently slow to permit of a separation of the crystallizing mass into portions of varying composition and that before the entire mass had solidified portions had become sufficiently solid to fracture, as a result of the stresses set up in the cooling and solidifying mass, and that the more fluid portions had been forced into these fractures and formed dikes. Mineral-

ization is also associated with these larger laccoliths. This occurs along fissures in the intrusive rock and in the sedimentary rocks adjacent to the intrusives. Such mineralization, as already noted, occurs only associated with the larger laccoliths and, as in the case of dikes, it seems a reasonable interpretation that the mineralizing solutions have separated from the crystallizing magma and entered along fissures in the solidified portions where they deposited the ore minerals. In some instances such solutions escaped into the adjacent sedimentary rocks where they formed the contact deposits.

On the assumption that the ore solutions have resulted from a differentiation of the magma within the laccolithic reservoirs, certain deductions concerning the probable size and abundance of ore deposits are possible.

As already pointed out, in the smaller outlying reservoirs the solidification was so rapid that there was little opportunity for a differentiation of the magma, and if such took place on a small scale there was little possibility of the different materials collecting in bodies of any considerable size. In the larger bodies where the solidification was slower the opportunity for separation was more favorable, but even in the largest bodies in the groups in southeastern Utah the solidification of a large part of the material entering a chamber must have been so rapid that there was little opportunity for differentiation, and for the remaining portion the conditions would not be favorable to a high degree of differentiation. It may be presumed then that in the crystallization and solidification of these rock masses only a small proportion of the metals have been expelled as compared with what would have been under conditions of slow crystallization giving ample time for separation and concentration of the different constituents.

It should be remembered also that laccolithic bodies are usually cut off from their deep-seated source so that there is no tendency to concentrate the more mobile substances resulting from deeper seated differentiation.

It is possible that in some cases movements of the rocks might keep the channel to the deeper igneous reservoir open, thus permitting the entrance of mobile constituents from below and the

formation of large ore deposits. No evidence indicating that this has taken place in any of the laccoliths under discussion is known.

If the above suppositions and deductions are correct the extent of the ore deposits associated with laccolithic bodies, other things being equal, is dependent on the size of the laccolith. If it is small there will likely be no mineralization, if very large, extensive deposits might be expected.

In the laccolithic groups of southeastern Utah the total amount of igneous material is considerable, but that contained in any individual laccolithic body is relatively small. From theoretical considerations, then, it is to be expected that only small metal deposits are present in these laccoliths.

Gilbert[7] many years ago arrived at essentially this conclusion though he based it on the belief that conditions were not favorable to the formation of fissures rather than on the considerations presented above. Since then prospecting has been carried on intermittently for nearly forty years, and many thousands of dollars have been expended in the search for and development of metalliferous veins. Such veins have been found and have yielded a small amount of gold, silver, and copper. Those developed to the present time are, however, relatively small and associated with weak fissuring and give little promise of yielding important amounts of metal. After nearly forty years Gilbert's prediction that "gold and silver will not be found in paying quantities in the laccolithic mountains, including the La Sal, Abajo, and Henry Mountains," seems to hold good. The foregoing statements, of course, apply only to lode deposits and do not include the sandstone and placer deposits in the vicinity of these mountain groups.

Stocks.—It is believed that the space occupied by the igneous material constituting the stocks was formed in large part by a pushing aside and doming of the earlier rocks, as has been shown by Boutwell[8] for the Park City district and by the writer for the Star district and is strongly indicated, though less easily demonstrated, for other districts. That there has been some stoping

[7] Gilbert, G. K., "Geology of the Henry Mountains," pp. 82–83, 151–152, 1877.

[8] Boutwell, J. M., and Woolsey, L. H., "Geology and Ore Deposits of the Park City District, Utah," U. S. Geol. Survey Prof. Paper 77, p. 96, 1912.

and assimilation of the invaded rocks especially associated with the deeper portions of the stocks, seems not improbable, though little evidence of it has been observed and it is not thought to have been an important factor.

The formation of the materials of the stocks as we now find them may be thought of as taking place in the following general manner, though the actual process was doubtless more complex.

After the intrusion had taken place crystallization of the fluid magma began or continued if crystallization had already begun. The higher portions of the intrusive bodies and those in the smaller masses would lose their heat most rapidly and crystallization take place most quickly so that the upper part of a body and the relatively small apophyses would undergo comparatively slight differentiation and would have become sufficiently solid to fracture while the deeper seated portions were still fluid. This presumes that the rocks of the apically-truncated stocks have a composition nearer that of the original magma than the deeper stocks, an assumption which seems to be borne out in a general way by a comparison with the laccoliths where differentiation was certainly slight. No laccolith has been found associated with a stock where a direct comparison would be warranted.

As crystallization proceeded slowly in the deeper zone there was a tendency for the heavy iron, magnesium, calcium, titanium minerals, which for the most part crystallized early, to sink through the magma and thus render the portion from which they were removed more siliceous.[9] At the same time water and other mineralizers were expelled from the crystallizing magma and these light and very mobile constituents with metals, sulphur, silica and other materials in solution had a tendency to move upward. This movement apparently took place through the fluid with no marked tendency to concentration, other than a convergence as the size of the stock decreased upward, or to migration into the enclosing walls. When a point was reached where the material was suffi-

[9] Bowen has recently shown that heavy minerals crystallizing from a silicate melt will readily sink through the liquid from which they are forming. Bowen, N. L., "Crystallization-Differentiation in Silicate Liquids," *Am. Jour. Sci.*, vol. 39, pp. 175–191, 1915.

ciently crystallized and solidified to fracture, these mobile constituents concentrated in the fractures and guided by them passed to cooler portions of the intrusive body or into the enclosing rocks. When a point was reached where the physical-chemical conditions were favorable to the precipitation of metals the formations of ore bodies began. In the intrusive bodies the high temperature type of deposits would first form as the tourmaline veins, and following them types of copper-gold and lead-silver veins indicative of lower temperature, and as the solutions passed from the intrusive bodies into the enclosing sedimentary and effusive rocks under differing chemical and physical environments, various types of deposits would be formed. Fig. 19 presents the general idea of the portions of the system from which most of the metals were derived and the places where they were precipitated.

If this interpretation of the process is correct one would expect to find instances where fractures in passing downward disappear at a zone where the material was too liquid to retain a fracture at the time they were formed. The fact that such conditions are not more often seen may be due to several causes, but perhaps the most important is that that zone was not favorable to extensive mineralization and there is little inducement to follow fissures into it. A particularly interesting example of the change of a fracture downward is seen in the Cactus mine in the San Francisco stock. At the surface this is a broad breccia zone, exceeding 100 feet in width and traceable along the strike for several thousand feet. In the downward extension there is a gradual but rather rapid contraction of the fissured zone and decrease in brecciation so that at a depth of 900 feet below the outcrop it has a width of but a few feet, shows little brecciation, and one can well imagine that at a few hundred feet greater depth it might disappear entirely. The early minerals of this deposit are of the high temperature type, such as would be expected at this zone. There are other deposits in the state where one would expect to find similar conditions, as in the pegmatitic tourmaline veins of the Clifton district, but developments have been too meager to reveal them. It may be noted also that somewhat similar conditions occur where pegmatitic gold-quartz veins of the

FIG. 19. Ideal section through the top portion of an intrusive body showing the portions where differentiation is more important and the places where the solutions precipitate metals. The lighter portions of the stocks are the more highly differentiated, at this horizon being most siliceous.

Ibapah and Raft River stocks pass into true pegmatite carrying no metals.

The most important deposits of the state are associated with igneous masses that have been eroded but a relatively short distance below their top, as those of the Park City, Bingham, Tintic, San Francisco districts, the Tushar Range and the Iron Springs district.

That deposits comparable in extent with these may have been associated with higher portions of the larger and more deeply eroded masses, seems entirely probable, but that such deposits will be found associated with the deeply eroded remnants now remaining seems highly improbable.

It is readily seen that this explanation supposes that there was a relatively greater expulsion of metallic constituents from the portions of the magmas that crystallized slowly than from those cooling rapidly near the surface, and that there was a transfer of metallic constituents from the deeper zone to points nearer the surface. That is, if the different rock bodies were to be sampled for their content of metal it would be found that the rock of the small laccoliths would be highest and would not differ materially from corresponding extrusive rocks. That of the large laccoliths would be less as part of the metals are collected in veins. The rocks of the apically-truncated stocks would doubtless be less than the laccoliths as the conditions under which they consolidated doubtless permitted of greater differentiation. The rocks of the deeper-truncated stocks would show least of all since there was ample opportunity for extensive differentiation and the metallic constituents tended to migrate toward the surface.

It is evident that in all cases the process was the same but differed in amount.

The general relations and processes here described have for the most part been recognized before but are especially well illustrated in the ore deposits of Utah and their commercial importance especially well shown.

Spencer[10] has pointed out that cross cutting intrusive bodies are

[10] Spencer, A. C., "Magnetite Deposits of the Cornwall Type in Pennsylvania," U. S. Geol. Survey Bull. 359, p. 16, 1908.

more favorable to ore deposition than sills on account of the more direct connection with the deep-seated source.

Ferguson and Bateman[11] have shown that tin deposits commonly occur near the top of granite bodies.

The general process of differentiation here suggested does not differ materially from those that have been previously suggested, notably by Spurr.[12] It does differ somewhat from the process which Umpleby[13] finds to best explain the deposits at Mackay, Idaho, which is that of "backward concentration." This postulates a constant tendency toward an inward and downward migration of the more mobile constituents with intermittent outward movements as against a constant upward movement.

In the preceding pages the stocks have been considered as apically-truncated and medially-truncated. It is obvious that no sharp line can be drawn between these, but for the purpose of description arbitrary distinction is made. A further subdivision of the apically-truncated stocks based on the character of the associated ore deposits is possible but is reserved for future presentation.

It is probable that the relations of the intrusive bodies in Utah are unusually simple, due perhaps to relatively stable conditions following the intrusions. If after the magma had been intruded and partially solidified and the still fluid part consisted of a siliceous portion underlying the solid and at greater depth perhaps a basic portion, an impulse was given from below, the fluid portions might be driven into or through the solidified portions or might even reach the surface as flows. Such conditions are undoubtedly present in Utah as is especially suggested by pegmatitic and basic dikes of the Granite Range, but for the most part they seem to have been of minor importance.

The application of the ideas presented above to other regions naturally suggests itself. In certain instances they seem to meet the conditions, while in others the application is not so obvious.

[11] Ferguson, H. G., and Bateman, A. M., "Geologic Features of Tin Deposits," ECONOMIC GEOLOGY, vol. 7, p. 223, 1912.

[12] Spurr, J. E., "Theory of Ore Deposition," ECONOMIC GEOLOGY, vol. 7, p. 485, 1912.

[13] Umpleby, J. B., "The Genesis of the Mackay Copper Deposits, Idaho," ECONOMIC GEOLOGY, vol. 9, p. 307, 1914.

While there is a temptation to extend the application it seems best to leave this to those most familiar with the different regions.

SUMMARY.

The larger intrusive bodies of Utah are of two types, laccoliths and stocks. The laccoliths occur in the sandy and shaly sediments in the southeastern part of the state, the stocks in the quartzites and limestones in the western part of the state.

The stocks may be subdivided into those truncated near the apex and those truncated at greater depth. The deeper truncated stocks are uniformly more siliceous. The apically-truncated stocks are monzonitic to dioritic in composition, the deeper truncated stocks have the composition of granodiorite to granite.

The ore deposits associated with the laccoliths and deeper truncated stocks have been of comparatively slight commercial importance, while associated with the apically-truncated stocks are deposits of great value.

It is believed that the lack of large deposits associated with the laccoliths is due to the fact that after intrusion they were sealed off from their deep-seated source and that the amount of material in the laccoliths themselves was too small and the differentiation on solidifying too incomplete to furnish large deposits.

It is believed that in the stocks the differentiation was greater at depth and that the mobile constituents of the magma, as the water and other mineralizers with metals, sulphur, etc., in solution, rose toward the surface, while the heavier minerals that crystallized early sank to greater depth. When the mobile constituents reached a point where the magma was sufficiently solidified to fracture they were guided by the fractures or fissures and on reaching favorable physical and chemical environments began to deposit the metals in solution. The deeper truncated stocks are regarded as probably remnants from which the portion in which the metals were concentrated has been eroded.

THE COMPOSITION OF WATERS IN MINES OF SULPHIDE ORES.

EDWIN T. HODGE

The deposition and superficial alteration of ore deposits are complex processes, and unlike many laboratory experiments the results cannot be reduced to simple chemical formulæ. Generally the investigator sees only the end products of the reactions: he does not supply the material nor does he determine the conditions that obtain. Geologic theory, therefore, has been built up mainly by inference or by testing repeatedly promising working hypotheses. Some of these hypotheses have been tested so often under widely differing conditions, and have been found applicable at so many places, that they have become accepted theories, if not indeed principles of geology. Thus it is incontrovertible that some sulphide ores have been deposited by cold circulating underground waters and that many have been enriched by solution and redeposition by ground waters in the superficial zone. One cannot estimate exactly the character of the waters that are the agents of superficial alteration and enrichment, but the best available index is to be found in the waters that are now circulating through sulphide ores and that may be collected in mines exploiting deposits of these ores. Some fifty analyses of waters from sulphide ores are available. They vary greatly in concentration and for that reason the constitution of the various waters is not readily compared. To facilitate such a comparison the analyses have been reduced to percentage of total solids, and the various radicles have been expressed as molecular or reacting values and arranged in groups intended to bring out these relations most clearly.

In table I.,[1] on pages 126–130 the analyses are numbered consecutively.

[1] 1, 2, 3, 4, 5, 6, 7, Butte, Montana. W. F. Hillebrand, analyst. Weed, W. H., "Geology and Ore Deposits of Butte District, Montana," Prof. Paper U. S. Geol. Survey No. 74, 1912, p. 101.

8, 9, 10, 11, 12, Capote Mine, Cananea, Mexico. G. W. Hawley, analyst

The columns designated "W" show percentage of total solids, and the column following, designated by "R. V.." shows the same analysis with radicles calculated to reacting values.[2]

The reacting value is the value obtained by dividing the percentage of a radicle by its equivalent weight. The valencies used are those of the oxides commonly assumed to be present in mine

Emmons, W. H., "The Enrichment of Sulphide Ores," Bull. U. S. Geol. Survey, No. 529, p. 60.

13, Burra Burra mine, Ducktown, Tenn., first level below black copper workings. R. C. Wells, analyst. Emmons, W. H., and Laney, F. B., "Preliminary Report on the Mineral Deposits of Ducktown, Tenn.," Bull. U. S. Geol. Survey, No. 470, 1911, pp. 171, 172.

14, 15, Callaway shaft, Ducktown, Tenn., at water level. R. C. Wells, analyst. Emmons and Laney, "Preliminary Report on the Mineral Deposits of Ducktown, Tenn.," Bull. U. S. Geol. Survey, No. 470, 1911, pp. 171–172.

16, East Tennessee mine, Ducktown, Tenn., R. C. Wells, analyst. Emmons and Laney, *idem.*

17, 18, Ducktown, W. H. Emmons, Bull. 529, U. S. G. S., p. 60.

19, Joplin, Mo., analyses by Buehler, H. A., and Gottschalk, V. A. "Data of Geochemistry," Clark, F. W.; Bull. U. S. Geol. Survey, No. 491.

20, Joplin, Mo. Analysis by H. N. Stokes. "Data of Geochemistry," *loc. cit.*

21, Joplin, Mo. "Data of Geochemistry," p. 177, *loc. cit.*

22, 23, 24, 25, Rothschönberger Stolln, Freiberg, Germany. A. Frenzel, analyst. Beck, Richard, "The Nature of Ore Deposits" (translated by W. H. Weed), Vol. 2, 1905, p. 377.

26, 27, 28, Hauraki, Auckland. "The Geology of the Waihi-Tairua Subdivision," Bell, J. M., and Fraser, Colin, Publications of New Zealand Geological Survey, No. 15.

29, Stanley mine, Idaho Springs, Colo. L. J. W. Jones, analyst. Jones, L. J. W., "Ferric Sulphate in Mine Waters and its Action on Metals," Proc. Colorado Sci. Soc., Vol. 6, 1897–1900, p. 48.

30, Mizpah mine, Tonopah, Nev., from bore hole 2,316 feet deep. R. C. Wells, analyst. Bull. U. S. G. S. 529, p. 631.

31, Savage mine (Comstock lode), Storey County, Nev., 600-foot level.

32, 33, Gould & Currey mine (Comstock lode), Storey County, Nev.

34, Hale & Norcross tunnel section (Comstock lode), Storey County, Nev.

35, C. & C. shaft (Comstock lode), Storey County, Nev., 2,250-foot level. N. E. Wilson, analyst. Reid, J. A., "The Structure and Genesis of the Comstock Lode," Bull. Dept. Geology Univ. California, Vol. 4, 1906, p. 189.

36, Central tunnel (Comstock lode), Storey County, Nev., vadose water. N. E. Wilson, analyst. Reid, J. A., *loc. cit.*, p. 192.

[2] Palmer, Chase, "Geochemical Interpretation of Water Analyses," Bull. U. S. Geol. Survey, No. 479, p. 7.

waters. The sum of the reacting values of all the positive ions should equal the sum of the reacting values of all the negative ions. Some analyses, however, when thus recalculated, will not balance. This is probably due in part to iron and aluminum oxides which are present to a greater or less extent as colloids and not as sulphates or other salts, and also to the failure on the part of the chemist to determine carbonates, hydroxides, and other radicles.

The reacting value enables one to determine the reaction of a water. Hydrolysis of a salt gives a solution which may be acid, neutral, or alkaline in reaction, depending upon the relative strength of the acids and bases which reacted to form the salt. Salts which are not hydrolized give neutral solutions. Therefore (I.)[3] those waters in which the strong acids (SO_4, Cl) are less than the alkalies are alkaline; (II.) those waters in which strong acids are equal to the alkalies are neutral; (III.) those waters in which strong acids are greater than the alkalies, but less than the sum of alkalies, earths, and metals, may be either neutral or acid, depending upon relative abundance of salts; and (IV., V.) those waters in which strong acids are equal to or greater than the

37, 38, Ely district, Nev., "Chalcocite Enrichment," Spencer, Arthur C., ECON. GEOL., Vol. 8, No. 7, 1913, p. 621.

39, Bachelor mine, Creede, Colo. Iron includes some aluminum. Water is alkaline. Chase Palmer, analyst.

40, Solomon mine, Creede, Colo. Iron includes some aluminum. Water is alkaline. Chase Palmer, analyst.

41, 42, Homestake mine, S. Dakota. W. J. Sharwood, ECON. GEOL., Vol. 6. 1911, p. 738.

44, Federal Loan mine, Nevada City, Cal., 400-foot level. W. F. Hillebrand, analyst. Lindgren, Waldemar, "The Gold-quartz Veins of Nevada City and Grass Valley, California," Seventeenth Ann. Rept. U. S. Geol. Survey, Pt. 2, 1896, p. 121.

45, Black Prince mine, Nevada City, Cal., 400-foot level. W. F. Hillebrand, analyst. Lindgren, *idem*.

46, Victoria Reef, "Western Australia Mineral Deposits," Lindgren, Waldemar.

47, 48, Geyser mine, Custer County, Colo. W. F. Hillebrand, analyst. Emmons, S. F., Seventeenth Ann. Rept. U. S. Geol. Survey, Pt. 2, 1896, p. 462.

49, 50, Sulphur Bank, California. Analyses by Melville, W. H. G. F. Becker, Mon. U. S. Geol. Survey, Vol. 13, 1888, p. 259.

[3] Numbers refer to Chase Palmer's classes.

TABLE I.

SHOWING COMPOSITION, REACTING VALUES, REACTION, CONCENTRATION, DEPTH, AND CLASSIFICATION OF WATERS FROM MINES OF SULPHIDE ORES.

	Mountain View.		St. Lawrence.		Green Mountain.		Nettie.		Gagnon.		Glengary.		Anaconda.		Capote.		Capote.		Capote.	
	1 W.	R. V.	2 W.	R. V.	3 W.	R. V.	4 W.	R. V.	5 W.	R. V.	6 W.	R. V.	7 W.	R. V.	8 W.	R. V.	9 W.	R. V.	10 W.	R. V.
SO_4	60.28	49.77	63.55	48.12	62.06	42.42	19.20	13.80	27.27	16.68	53.84	38.60	41.62	30.09	65.02	52.12	68.85	53.43	67.71	57.19
Cl	.02	.02	.31	.32	1.04	.96	4.29	4.18	38.72	32.08	11.70	11.37	5.42	5.31	undetermined		.....	.....	.33	.34
CO_3	.....	.....	.....	.....	2.02	2.21	37.13	42.72	.....	.....	.....	.....	.....	?	.....	.....	.....	.....	.....	.....
SiO_2	.06	.....	1.13	.....	3.54	.....	15.93	.....	1.36	.....	2.68	.....	16.58	.....	.96	.....	.71	.....	.86	.....
NO_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
B_4O_7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
H	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Na	.04	.07	.94	1.49	2.47	3.51	8.60	2.93	3.81	4.87	17.49	26.22	5.10	7.71	undetermined		1.71	2.20	3.01	3.77
K	.01	.01	.31	.29	1.08	.91	1.43	1.26	.52	.39	3.01	2.66	1.61	1.43	.....	.....				
Li	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
NH_4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mg	.14	.46	1.47	4.40	4.31	11.65	1.91	5.43	4.71	11.39	1.77	5.01	4.73	13.52	.77	2.44	1.45	4.45	1.31	3.91
Ca	.26	.52	3.15	5.72	23.08	37.85	11.17	19.25	23.53	34.51	9.16	15.75	22.51	39.14	5.50	10.58	4.22	7.86	11.44	20.74
Sr	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mn	.01	.....	.28	.37	.08	.10	.23	.29	.06	.06	.....	.....	1.15	1.46	2.98	4.18	2.65	3.60	2.32	3.07
Al	.07	.31	1.99	8.02	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	undetermined		.78	3.22	.33	1.33
Fe'''	.....	.....	3.80	6.19	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Fe''	.04	.06	.....	.....	.27	.32	.11	.14	.02	.02	.14	.17	.41	.51	3.85	5.31	14.11	18.86	7.95	10.35
Cu	38.72	48.35	1.41	1.61	.....	.....	.....	.....	.....	.....	.03	.03	.....	.....	20.92	25.37	2.16	2.54	.91	1.04
Zn	.35	.43	20.27	22.59	.05	.05	.....	.....	.....	.....	.18	.19	.87	.93	undetermined		3.36	3.84	3.83	4.26
Cd	.....	.....	.97	.63	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Sn	.....	.....	.41	.25	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Ni-Co	.....	.....	.01	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Pb	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Traces	Ni, PO_4Co, Li, As_3O_4, Ti, C		PO_4, Br, B_4O_7, F		PO_4, Cu, Li, As_3O_4		Zn, PO_4, C		PO_4, Cu, CO_2		PO_4, CO_2 Pb, As_3O_4, S, C		PO_4CO_2		.....		.....		.....	
Grm. per liter	117.846		4.2045		.655		.3501		2.1764		1.012		.2171		7.932		5.661		6.583	
Reaction	III acid		III acid		III neutral		III neutral		III faint. alk.		IV faint alk.		III faint. alk.		IV acid		V acid		V acid	
Class	A		A		B		B?		B		B		B		A		A		A	
Depth	200′		1,200′		2,200′		300′		1,800′		.....		.....		300′		pump		900′	
Country Rock	Quartz Monzonite				Quartz Monzonite				Quartz Monzonite				Q. Monzonite		Quartz Diorite		Quartz Diorite		Quartz Diorite	

TABLE I.—*Continued.*

	Capote.		Capote.		Burra Burra.		Calloway.		Calloway.		East Tennessee.		Ducktown.		Ducktown.		Victor.		Alabama Coon.	
	11 W.	R. V.	12 W.	R. V.	13 W.	R. V.	14 W.	R. V.	15 W.	R. V.	16 W.	R. V.	17 W.	R. V.	18 W.	R. V.	19 W.	R. V.	20 W.	R. V.
SO_4	68.85	53.43	67.71	57.19	60.28	49.77	63.55	48.12	62.06	42.42	19.20	13.80	27.27	16.68	53.84	38.60	41.62	30.09	65.02	52.12
Cl	.....	.....	.33	.34	.02	.02	.31	.32	1.04	.96	4.29	4.18	38.72	32.08	11.70	11.37	5.42	5.31	undetermined	
CO_3	.....	.....	.....	.....	.....	.....	.....	.....	2.02	2.21	37.13	42.72	.....	.....	.....	.....	.....	?	.....	.....
SiO_2	.71	.....	.86	.....	.06	.....	1.13	.....	3.54	.....	15.93	.....	1.36	.....	2.68	.....	16.58	.....	.96	.....
NO_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
B_4O_7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
H	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Na	1.71	2.20	3.01	3.77	.04	.07	.94	1.49	2.47	3.51	8.60	2.93	3.81	4.87	17.49	26.22	5.10	7.71	undetermined	
K					.01	.01	.31	.29	1.08	.91	1.43	1.26	.52	.39	3.01	2.66	1.61	1.43	.....	.....
Li	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
NH_4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mg	1.45	4.45	1.31	3.91	.14	.46	1.47	4.40	4.31	11.65	1.91	5.43	4.71	11.39	1.77	5.01	4.73	13.52	.77	2.44
Ca	4.22	7.86	11.44	20.74	.26	.52	3.15	5.72	23.08	37.85	11.17	19.25	23.53	34.51	9.16	15.75	22.51	39.14	5.50	10.58
Sr	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mn	2.65	3.60	2.32	3.07	.01	.....	.28	.37	.08	.10	.23	.29	.06	.06	.....	.....	1.15	1.46	2.98	4.18
Al	.78	3.22	.33	1.33	.07	.31	1.99	8.02	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	undetermined	
Fe'''	.....	.....	.....	.....	.....	.....	3.80	6.19	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Fe''	14.11	18.86	7.95	10.35	.04	.06	.....	.....	.27	.32	.11	.14	.02	.02	.14	.17	.41	.51	3.85	5.31
Cu	2.16	2.54	.91	1.04	38.72	48.35	1.41	1.61	.....	.....	.....	.....	.....	.....	.03	.03	.....	.....	20.92	25.37
Zn	3.36	3.84	3.83	4.26	.35	.43	20.27	22.59	.05	.05	.....	.....	.....	.....	.18	.19	.87	.93	undetermined	
Cd	.....	.....	.....	.....	.....	.....	.97	.63	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Sn	.....	.....	.....	.....	.....	.....	.41	.25	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Ni-Co	.....	.....	.....	.....	.....	.....	.01	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Pb	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Traces	.....		.....		Ni, PO_4Co, Li, As_3O_4, Ti, C		PO_4, Br, B_4O_7, F		PO_4, Cu, Li, As_3O_4		Zn, PO_4, C		PO_4, Cu, CO_2		PO_4, CO_2 Pb, As_3O_4, S, C		PO_4CO_2		.....	
Grm. per liter	7.932		5.661		117.846		4.2045		.655		.3501		2.1764		1.012		.2171		6.583	
Reaction	IV acid		V acid		III acid		III acid		III neutral		III neutral		III faint. alk.		IV faint alk.		III faint. alk.		V acid	
Class	A		A		A		A		B		B?		B		B		B		A	
Depth	300′		pump		200′		1,200′		2,200′		300′		1,800′		.....		.....		900′	
Country Rock	Quartz Diorite		Quartz Diorite		Quartz Monzonite				Quartz Monzonite				Quartz Monzonite				Q. Monzonite		Quartz Diorite	

Depth	200′	1,200′	2,200′	300′	1,800′												pump	900′		
Country Rock	Quartz Monzonite		Quartz Monzonite		Quartz Monzonite						Q. Monzonite		Quartz Diorite		Quartz Diorite		Quartz Diorite			

TABLE I.—*Continued.*

	Capote.		Capote.		Burra Burra.		Calloway.		Calloway.		East Tennessee.		Ducktown.		Ducktown.		Victor.		Alabama Coon.	
	11 W.	R. V.	12 W.	R. V.	13 W.	R. V.	14 W.	R. V.	15 W.	R. V.	16 W.	R. V.	17 W.	R. V.	18 W.	R. V.	19 W.	R. V.	20 W.	R. V.
SO_4	64.73	46.90	66.52	47.69	67.09	49.04	74.96	61.91	67.72	51.80	74.51	51.23	77.88	53.80	78.89	56.54	68.85	56.21	63.25	49.11
Cl	.82	.81	.....	.....	.....	.....	.08	.09	.05	.05	.07	.07	.09	.08	.10	.10	.13	.13	.03	.03
Co_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
SiO_2	1.28	.....	1.00	.....	.55	.....	4.46	.....	5.92	.....	2.38	.....	2.81	.....	2.96	.....	.84	.....	1.11	.....
NO_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
B_4O_7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
H	.....	.....	.....	.....	.03	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.19	.....	.....	.....
Na	7.76	9.35	.70	.83	.23	.34	.64	1.11	.65	1.04	.18	.26	.44	.64	.44	.66	.47	.71	.51	.83
K					.20	.18	.33	.34	.26	.25	.24	.20	.41	.35	.46	.41	.12	.11	.01	.01
Li	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
HN_4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mg	1.64	4.71	2.69	7.76	.40	1.13	.64	2.09	.73	2.21	1.90	5.16	1.69	4.61	1.75	4.96	1.77	5.05	.26	.78
Ca	14.55	25.36	13.80	23.72	.67	1.15	2.38	4.71	3.60	6.60	7.19	11.86	2.71	4.49	2.60	4.47	9.47	16.39	3.55	6.61
Sr	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mn	1.69	2.15	2.24	2.81	.....	.....	.02	.03	.01	.01	.01	.01	.13	.16	.04	.05	.....	.....	.02	.02
Al	.73	2.82	.45	1.71	4.28	16.29	1.75	7.69	2.26	9.19	4.98	18.21	6.84	25.16	5.75	21.93	.43	1.65	1.46	6.03
Fe‴	.....	.....	1.20	2.22	.....	.....	2.45	5.22	6.61	13.07	5.63	10.01	4.61	8.23	4.29	7.95	.....	.....	4.88	8.16
Fe″	3.47	4.34	7.42	9.15	21.50	26.46	8.61	12.23	10.55	13.90	.04	.05	.....	.....	.....	.....	5.19	6.45		
Cu	.....	.....	1.39	1.51	3.08	3.33	3.39	4.23	1.30	1.50	1.23	1.28	1.77	1.85	1.84	2.00	.....	.....	.04	.05
Zn	3.33	3.56	2.59	2.73	1.98	2.08	.29	.35	.34	.38	1.64	1.66	.62	.63	.88	.93	12.54	13 30	24.79	28.31
Cd	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.09	.06
Sn	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Ni-Co	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Pb	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Traces	.....		.....		Mn, Cl		.....		.....		.....		Fe″		Fe″		.....		.....	
Gm. per liter	2.192		2.007		10.1238		.8291		.8451		3.3102		.6794		.697		2.751		9.7275	
Reaction	III neutral		III neutral?		III acid		V acid		V acid		V acid		V acid		V acid		IV. acid?		III acid	
Class	A or B		A or B		A		A		A		A		A		A		A		A	
Depth	400′		concentrator		100′		90′		127′		180′		55′ below water level		surface		.....		.....	
Country Rock	Quartz Diorite		Quartz Diorite		Schists and graywacke				Schists and graywacke				Schists and graywacke				Limestone		Limestone	

TABLE I.—*Continued.*

	Shoal Creek.		Rothschönberger.		Rothschönberger.		Rothschönberger.		Rothschönberger.		Waihi-Tairua.		Waihi-Tairua.		Waihi-Tairua.		Stanley.		Mizpah.	
	21 W.	R. V.	22 W.	R. V	23 W.	R. V.	24 W.	R. V.	25 W.	R. V.	26 W.	R. V.	27 W.	R. V.	28 W.	R. V.	29 W.	R. V.	30 W.	R. V.
SO_4	52.76	39.82	57.94	28.64	58.85	27.67	48.33	24.71	62.98	29.04	23.96	15.38	5.86	4.04	24.32	16.04	67.95	49.90	43.96	31.87
Cl	.48	.49	.....	.....	.....	.....	5.88	4.08	.....	.....	5.71	7.62	7.32	6.83	5.31	4.75	.27	.27	4.78	4.70
CO_3	8.00	9.67	.....	.....	.....	.....	.....	.....	.....	.....	35.43	36.37	44.33	48.86	35.23	37.18	.....	.....	11.81	13.71
SiO_2	2.54	.....	2.13	.....	2.27	.....	8.54	.....	.63	.....	6.33	.....	10.57	.....	7.24	.....	1.45	.....	8.71	.....
NO_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
B_4O_7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
H	.....	.....	1.20	28.28	1.21	27.13	1.00	24.39	1.34	29.45	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Na	.67	1.06	.....	.....	.....	.....	.....	.....	.....	.....	7.28	9.77	10.86	15.64	7.17	9.90	3.54	5.44	20.00	30.31
K	.46	.43	.....	.....	.....	.....	.....	.....	.....	.....	5.26	4.15	7.08	6.00	4.20	3.42	2.33	2.11	.46	.41
Li	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
HN_4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mg	.71	2.12	3.96	7.73	4.41	8.19	6.88	13.90	3.90	7.11	.95	2.41	1.71	4.66	1.01	2.63	3.12	9.05	.85	2.43
Ca	11.32	20.50	19.28	22.85	27.33	30.83	22.02	27.00	27.05	29.90	14.05	21.56	11.63	12.12	14.24	22.52	6.24	10.99	9.25	16.08
Sr	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mn	.42	.56	1.10	.95	.48	.40	.....	.....	1.41	1.17	.....	.....	.....	.....	.....	.....	5.18	6.66	.....	.....
Al	.08	.32	.10	.26	.38	.95	.....	.....	.44	1.08	.66	2.25	.44	1.61	.89	3.12	.10	.39	.09	.35
Fe‴	.....	.....	1.68	2.15	1.21	1.47	.....	.....	1.41	1.68	.....	.....	.....	.....	.....	.....	5.49	10.42	.09	.14
Fe″	.11	.14	.....	.....	.....	.....	3.13	2.75	.....	.....	.37	.49	.20	.24	.39	.44	.11	.14		
Cu	.04	.05	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	2.57	2.85	.....	....
Zn	22.31	24.78	12.61	9.14	4.86	3.36	4.22	3.17	.84	.57	.....	.....	.....	.....	.....	.....	1.65	1.78	.....	....
Cd	.10	.06	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	....
Sn	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	....
Ni-Co	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	....
Pb	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Traces	.....		Ni, Co, Cl		Ni, Co, Cl		Cl		Ni, Co, Cl		.....		.....		.....		.....		NO_3, Zn	
Gm. per liter	.540		.37597		.38848		.2108		.33563		.03156		.02459		.04143		3.00206		.7442	
Reaction	III acid?		III acid		III acid		III acid		III acid		III faintly acid		III alkaline?		III neutral		V acid		III neutral	
Class	B		A		A		A		A		B		B		B		A		D	
Depth	.....		.....		.....		Surface				1,150′		deep		1040′		.....		2316′	
Country Rock	Limestone		Biotite schist		Biotite schist		Biotite schist		Biotite schist		Andesite and Dacite						Granite		Rhyolite	

TABLE I.—*Continued.*

	Savage.		Gould-Curry.		Gould-Curry		Hale-Norcross.		C. and C.		Central Tunnel.		Ruth.		Brooks Porphyry.		Bachelor.		Solomon.	
	31 W.	R. V.	32 W.	R. V.	33 W.	R. V.	34 W.	R. V.	35 W.	R. V.	36 W.	R. V.	37 W.	R. V.	38 W.	R. V.	39 W.	R. V.	40 W.	R. V.
SO_4	58.50	39.56	58.50	39.56	58.50	39.56	58.50	39.56	58.50	39.56	58.50	39.56	58.50	39.56	58.50	39.56	58.50	39.56	58.50	39.56
Cl	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52
CO_3	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52
SiO_2	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52
NO_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
B_4O_7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
H	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Na	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52
K	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52
Li	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
HN_4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mg	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52
Ca	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52
Sr	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mn	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52
Al	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52
Fe‴	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Fe″	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52
Cu	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52
Zn	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52	1.50	1.52
Cd	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Sn	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Ni-Co	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Pb	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Traces	.....		.....		.....		.....		.....		.....		.....		.....		.....		.....	
Gm. per liter	.....		.....		.....		.....		.....		.....		.....		.....		.....		.....	
Reaction	.....		.....		.....		.....		.....		.....		.....		.....		.....		.....	
Class	.....		.....		.....		.....		.....		.....		.....		.....		.....		.....	
Depth	.....		.....		.....		.....		.....		.....		.....		.....		.....		.....	
Country Rock	.....		.....		.....		.....		.....		.....		.....		.....		.....		.....	

Depth	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Country Rock	Limestone		Biotite schist		Biotite schist		Biotite schist		Biotite schist		Andesite and Dacite						Granite		Rhyolite	

TABLE I.—*Continued.*

	Savage.		Gould-Curry.		Gould-Curry		Hale-Norcross.		C. and C.		Central Tunnel.		Ruth.		Brooks Porphyry.		Bachelor.		Solomon.	
	31 W.	R. V.	32 W.	R. V.	33 W.	R. V.	34 W.	R. V.	35 W.	R. V.	36 W.	R. V.	37 W.	R. V.	38 W.	R. V.	39 W.	R. V.	40 W.	R. V.
SO_4	42.52	22.93	43.96	34.59	20.34	15.61	34.52	25.60	50.10	40.83	89.37	68.40	56.94	44.05	49.09	33.76	27.08	20.19	35.99	24.79
Cl	.14	.10	.13	.14	2.14	2.23	1.75	1.76	2.01	2.23	.05	.05	5.67	5.94	1.63	1.52	.....	.....	.55	.51
CO_2	12.85	11.09	12.10	15.22	24.76	30.40	30.60	36.31	21.16	2.82	.....	.....	.....	.....	7.29	8.02	35.28	42.08	31.85	35.11
SiO_2	3.41	.....	9.60	.....	8.76	.....	7.60	.....	14.10	.....	.26	.....	9.63	.....	5.37	.....	14.53	.....	7.99	.....
NO_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
B_4O_7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
H	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Na	6.38	7.19	.07	.12	1.00	1.60	.87	1.35	13.95	23.71	.23	.37	3.38	5.46	6.71	9.65	12.85	20.04	2.58	3.72
K	.94	.62	15.79	15.30	32.31	30.49	10.25	9.35	5.65	5.66	.....	.....	2.83	2.69	2.11	1.79	1.09	1.00	1.21	1.03
Li	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
NH_4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mg	17.21	36.67	.....	.....	.....	.....	.....	.....	.63	2.03	2.82	8.53	2.69	8.22	.....	.....	.58	1.71	2.52	6.86
Ca	16.55	21.40	18.35	34.63	10.69	19.67	14.41	25.63	10.58	20.67	.55	1.01	10.83	20.09	24.16	39.87	7.82	13.98	15.92	26.31
Sr	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mn	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.38	.51	.....	.....	.....	.....	.11	.15	1.10	1.33
Al	.....	.....	.....	.....	.....	.....	.....	.....	.15	.65	4.13	16.81	.....	.....	.....	.....	.....	.....	.....	.....
Fe'''	.....	.....	.....	.....	.....	.....	.....	.....	.67	1.41	2.15	4.25	3.30	8.59	}		.....	.....	.....	.....
Fe''	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	4.73	4.96	3.64	5.39	.66	.85	.29	.34
Cu	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.06	.07	.....	.....	.....	.....	.....	.....	.....	.....
Zn	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Cd	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Sn	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Ni-Co	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Pb	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Traces	.....		Fe		Fe		Fe		Au, Ag		Au, Ag		.....		.....		Cl, Al		Al	
Gm. per liter	.89483		.39439		.78646		.78888		.94593		233.9822		.9764		.5215		.22198		.29015	
Reaction	III neutral		III neutral		I alkaline		III neutral		III neutral		V acid		IVfaintlyacid?		III neutral		I alkaline		IV neutral	
Class	B		D		D		D		D		A		A or B		B		D		B	
Depth	600′		1700′		1800′		.....		2150′		deep		335′		250′		.....		.....	
Country Rock	Diabase and Diorite				Diabase and Diorite				Diabase and Diorite				Porphyry		Porphyry		Rhyolite		Rhyolite	

TABLE I.—*Concluded.*

	Homestake.		Homestake.		Homestake.		Federal Loan.		Black Prince.		Victoria Reef.		Geyser.		Geyser.		Sulphur Bank.		Sulphur Bank.	
	[41] W.	R. V.	[42] W.	R. V.	[43] W.	R. V.	[44] W.	R. V.	[45] W.	R. V.	[46] W.	R. V.	[47] W.	R. V.	[48] W.	R. V.	[49] W.	R. V.	[50] W.	R. V.
SO_4	34.03	20.02	61.98	40.44	27.32	17.47	3.19	2.03	2.95	2.10	3.17	1.89	5.15	2.85	15.10	9.33	10.06	8.13	.32	.23
Cl	2.40	1.91	1.44	1.27	3.11	2.70	1.31	1.13	1.17	1.42	49.14	39.69	5.93	4.45	2.76	2.31	14.39	15.76	13.57	12.69
CO_3	29.05	27.36	6.19	6.46	22.76	23.82	58.70	59.63	55.38	63.06	7.95	7.58	48.15	42.70	38.61	38.16	4.73	6.12	22.38	24.70
SiO_2	2.62	.....	.34	.....	1.15	.....	13.54	.....	15.63	.....	1.33	.....	.78	.....	9.04	.....	.90	.....	.73	.....
NO_3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.05	.02	.....	.....	.....	.....	.....	.....
B_4O_7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	40.09	19.98	27.98	11.90
H	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Na	4.37	5.37	} 2.47	2.67	14.70	19.64	5.55	7.37	5.17	7.69	34.40	42.86	22.89	26.53	12.72	16.43	28.49	48.17	33.97	49.00
K	1.77	1.28			19.98	15.72	.41	.32	.60	.53	.....	.....	6.31	4.30	3.70	2.81	.84	.84	.48	.41
Li	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.09	.35	.....	.....	.....	.....	.....	.....
NH_4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.02	.04	.05	.09
Mg	8.10	18.83	5.14	13.24	3.44	8.69	2.36	5.92	1.27	3.57	.82	1.93	5.66	12.39	4.28	10.45	.03	.10	.11	.30
Ca	17.31	24.42	22.49	35.92	7.14	10.95	13.91	21.17	16.75	18.03	3.08	4.40	4.66	6.19	13.06	19.35	.44	.85	.41	.68
Sr	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.06	.04	.....	.....	.....	.....	.....	.....
Mn	.....	.....	.....	.....	.....	.....	.11	.12	.....	.....	.....	.....	.02	.02	.28	.30	.....	.....	.....	.....
Al	} .35	.81	.....	.....	} .40	1.01	} .92	2.31	} .72	2.37	.05	1.59	.03	.01	.14	.48	.....	.....	.....	.....
Fe‴			.....	.....																
Fe″	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.06	.06	} .11	.13	} .24	.32	.....	.....	.....	.....
Cu	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.01	.01	.....	.....
Zn	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.01	.01	.07	.06	.....	.....	.....	.....
Cd	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Sn	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Ni-*Bo*	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Pb	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.04	.01	.....	.....	.....	.....	.....	.....
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Traces	.....		.....		.....		Mn, H_2S, Pb, C		Pb, C		.....		Br, I, F, PO_4		Cu, Li, Pb, CO_2. PO_4		H_2S		.....	
Gm. per liter	.45866		1.17965		.61073		.24156		.26476		1.6148		3.14073		.28625		4.632		5.096	
Reaction	III neutral		III neutral		I alkaline		I alkaline		I alkaline		I alkaline		I alkaline		I alkaline		I alkaline		I alkaline	
Class	B		B		D		C		C		C		D		D		D		D	
Depth	300′		1,100′		1550′		400′		400′		4280		.....		500′		.....		.....	
Country Rock	Schist		Schist		Schist		Granite		Granite		Sandstone		Rhyolite		Rhyolite		Basalt		Basalt	

alkalies, earths, and metals, are acid in reaction. The reaction is stated beneath each analysis. When the 50 analyses are recalculated in accordance with the above considerations, 22 are acid, 14 are neutral, and 14 are alkaline. Results obtained by these recalculations do not always agree with the reactions stated by the chemist.

CLASSES OF MINE WATERS.

A survey of the chemical composition, concentration, reaction, environment, associated rocks, and temperatures of the waters in Table I. reveals five classes of mine waters.

Class A.—The waters of this class are all acid in reaction. While a few contain free H_2SO_4, the reaction of most of the waters is due to the hydrolization of the salts of H_2SO_4 and, to a very small extent, to the salts of HCl. Salts of other acids are present only in traces. The salts of iron, copper and zinc are the only salts present in large amounts whose hydrolysis will produce an acid solution. Of these, the salts of iron are present in nearly all, the salts of zinc are found in only 19, and of copper in 15.

The compounds making up the bulk of the solids of Class A waters are mainly sulphates of calcium and of the heavy metals. Sulphates and chlorides of magnesium, sodium, and potassium are generally present in small amounts. Carbonates are not present in these acid solutions. Aluminum is present in large percentages in all, and manganese is generally present in large amounts. The percentage of colloidal silica is generally low. The concentration averages 2.96 grams per liter, when the Mountain View and Central Tunnel waters are excepted. This concentration is above that of any other class.

The following are waters typical of this class: Mountain View (1), and St. Lawrence (2), from Butte, Montana; Capote, (8), (9), (10), Central Tunnel (36), Stanley (29), Burra Burra (13), and Callaway (14), (15), at Ducktown; Victor (19), Alabama Coon (20), near Joplin, Mo.; Rothschönberger Stolln (22), (23), (24), (25) at Freiberg, Germany; and probably also Shoal Creek (21), Capote (11), (12) and Ruth (37).

These waters are carriers in the processes of sulphide enrich-

Depth	300'	1,100'	1550'	400'	400'	4286	300'	300'	Basalt
Country Rock	Schist	Schist	Schist	Granite	Granite	Sandstone	Rhyolite	Rhyolite	Basalt

ment. All occur in deposits rich in sulphides, particularly in either pyrite, or pyrrhotite or marcasite, and probably all were collected either in the zone of oxidation or not far below ground water level.

Class B.—Generally the waters of this class are neutral, but a few are faintly alkaline, or faintly acid. Calcium sulphate is the dominant salt. It is probably formed by reaction between calcite or feldspar and H_2SO_4, $CuSO_4$, or other metallic sulphates. Sulphates, chlorides, and carbonates of magnesium and sodium are present in all, with a less amount of potassium sulphates. Salts of aluminum are present in small quantities. Traces or small percentages of copper, zinc, lithium, arsenic, lead, and phosphorus are often present. Colloidal silica is relatively higher than in Class A. The concentration is variable. Waters illustrating this class are: Green Mountain (3), Brook's Porphyry (38), and Homestake (42). The inferences are that these waters were collected either below ground water level or at great depths.

There are two variations of Class B. One shows a large increase in NaCl. This is illustrated by several waters from Butte, viz., Gagnon (5), Glengarry (6), and Anaconda (7). It does not seem probable that the high chlorine content is due to aridity nor to the leaching of the surrounding rock, nor yet to the excreta of men and horses, because other Butte waters, probably formed similarly except as to depth, show a low NaCl content. The source of the NaCl is doubtful;[4] perhaps it is a contamination by a foreign water from a deep source.

A second group contains $CaCO_3$ in appreciable amounts. Calcium carbonate is soluble only in waters containing CO_2, a fact which indicates that these waters are not associated with iron sulphides under conditions which would produce acidity. The Solomon (40) and Homestake (41) belong here, as do probably the waters of Shoal Creek (21), Nettie (4), and Waihi-Tairua (26), (28).

Class C.—These waters closely resemble the vadose waters

[4] Lane, Alfred C., "Mine Water Composition," ECONOMIC GEOLOGY, Vol. IX., No. 3, April, 1914, p. 256.

from regions of little or no sulphides. In the waters of this class collected near the surface $CaCO_3$ is plentiful. If collected at depths, NaCl is generally abundant. In either case sulphates, carbonates, and chlorides of sodium, magnesium, manganese, aluminum, and iron are present. Colloidal silica is relatively high. The concentration is low and the reaction of all these waters is alkaline. The Federal Loan (44), Black Prince (45), Victoria Reef (46) are examples of this class.

Class D.—These waters are all alkaline, ascending, and some of them are hot. They are associated with recent igneous rocks. Borates or carbonates of sodium are the principal salts. Calcium and magnesium salts and silica are present in small amounts. Hydrogen sulphide is often present. Other elements frequently present are fluorine, nitrogen, and strontium. The concentration is variable. This class has been discussed at length by Emmons and Harrington.[5] The waters of Sulphur Bank (49), (50), and Geyser (47) belong to this class.

Class E.[6]—These waters are neutral or alkaline. They are chiefly solutions of sulphates and carbonates of sodium, potassium and calcium. Magnesium salts are usually present. Salts of manganese, aluminum, and iron are often present. The percentage of silica is high. The concentration is not above one gram per liter. These waters combine the chemical characters of Class D with those of preceding classes. They are often associated with thermal springs in regions of recent igneous rock. The composition suggests the possibility that these waters are mixtures of descending vadose waters with ascending thermal alkaline waters. The Savage (31), Bachelor (39), Gould and Curry (32), (33), Hale and Norcross (34), and probably Homestake (43), and Waihi-Tairua (27), belong to this class. All these are found in regions of late Tertiary vulcanism, although one, from the Homestake, was found in pre-Cambrian rocks which are cut by Tertiary intrusives.

In general these classes might suggest the work done by each water. Class A is the transporting agent in processes of sulphide

[5] Emmons, W. H., and Harrington, G. L., ECON. GEOL., Vol. 8, 1913, p. 653.
[6] Lindgren, W., "Mineral Deposits," p. 42.

enrichment. Class B results from Class A when waters of Class A have been depleted of their metallic salts. Class C is the type of water occurring in sulphide mines which probably does not accomplish much enrichment. Class D, mingling with the waters of Class A, produces waters of Class E, in consequence of which the salts of the metals are precipitated.

OBSERVATIONS ON TABLE I.

Inspection of Table I. reveals several interesting facts. We may first consider zinc and copper. Of the three acid solutions in which zinc is absent (26, 36, 37), one is practically neutral, and two are from deposits nearly free of zinc minerals. The acid waters lacking copper (19, 22, 23, 24, 25, 26, 37) are from mines nearly free of copper ores, or in which copper is very subordinate. Because of the high concentration of the sulphate radicle in acid solutions, most of the copper is present as $CuSO_4$.

Gold and silver are found in traces in the Central Tunnel and C. and C. waters of the Comstock Lode. Both contain ferric iron, probably as ferric chloride, since both solutions contain the chlorine radicle in abundance. One of these solutions is acid and the other is neutral. The acid solution contains no manganese notwithstanding the fact that the ores are highly manganiferous.

The lead radicle is found only in carbonate waters of alkaline reaction, doubtless it is present as $PbCO_3$.

The concentration of aluminum salts decreases decidedly with decreasing acidity. When aluminum is present the sulphate radicle is high, indicating that the salt is usually present as $Al_2(SO_4)_3$, although small amounts may be present as the colloidal hydroxide. Since the affinity constants for iron, copper, and zinc are higher than for aluminum, any free H_2SO_4 in the water would first form sulphates of those metals before forming aluminum sulphate. Only if an excess of acid was present over that necessary to combine with the metals would the feldspars, sericite, etc., be rapidly attacked to form $Al_2(SO_4)_3$. That this is often the case is shown by the association of the Comstock, Waihi-Tairua, Capote, and Tonopah waters, with large amounts of kaolinitic material.

In all neutral or alkaline solutions, when manganese is present, the iron is generally in the ferrous state. Ferric iron is found in several of these neutral or alkaline solutions, undoubtedly as a hydroxide.

Cadmium salts occur in two acid waters which contain zinc. Cadmium, tin, nickel, and cobalt occur in small amounts and only in acid solutions.

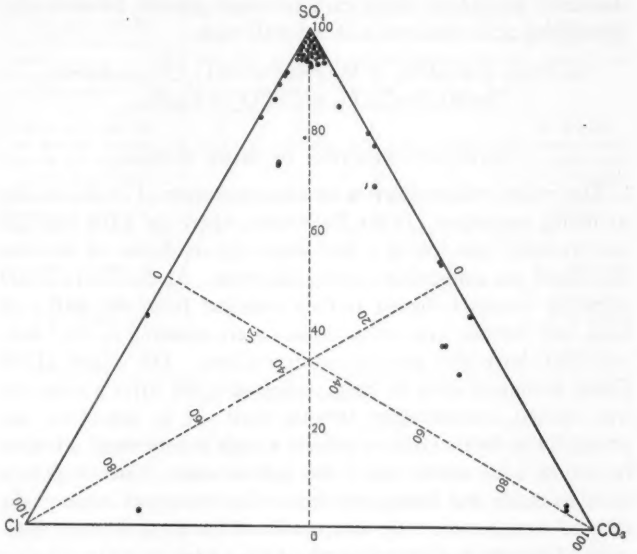

FIG. 20. Diagram showing the relative abundance of SO_4, Cl and CO_3 in 50 mine waters.

The relative abundance of the sulphate, chloride, and carbonate radicles in these waters is shown in Fig. 20. Sulphates are low and carbonates and chlorides correspondingly high in waters high in sodium, potassium, calcium, and magnesium. Silica is always present in colloidal form.

Some of these waters contain free H_2SO_4, which will react with many sulphides to generate H_2S. Alkaline sulphides are

found in some ascending thermal waters of Class D. When such waters as these mix with vadose acid waters to produce waters of Class E, the sulphates of the heavy metals will be precipitated.[7] Many of the waters show an increase in calcium and magnesium sulphate accompanying the decrease in the salts of the heavy metals. This indicates that in some cases the acid waters react with carbonate minerals. Reactions like the following undoubtedly take place, where carbonates are present, between most descending acid solutions and the wall rock.

$$2CuSO_4 + 2CaCO_3 + H_2O = Cu(OH)_2CO_3 + CaSO_4,$$
$$ZnSO_4 + CaCO_3 = ZnCO_3 + CaSO_4.$$

STATE OF OXIDATION OF MINE WATERS.

The waters collected are in an abnormal state of oxidation due to mining operations. In the Ruth mine, where the water level has been reduced 300 feet in a few years, the oxidation of the ores has raised the temperature several degrees. At the Burra Burra mine the waters collected as they emerged from the wall rock have only ferrous iron, while those waters standing in the Callaway shaft have both ferrous and ferric iron. The waters of the Green Mountain mine at Butte, collected a day after a cross cut was opened, contain only ferrous iron. It is, therefore, not probable that ferric salts are present except in very small amounts in normal mine waters below the vadose zone. Since H_2S oxidizes so easily and disappears from mine waters so rapidly, the salts of iron are the only compounds which form a ready indicator of the state of oxidation of a mine water.

CHANGES WITH ACIDITY AND DEPTH.

The average total concentration of acid solutions is 2.96 grams per liter, of neutral solutions the concentration is .82 gram per liter, of alkaline solutions it is .66 gram per liter. In these averages the Mountain View (1), at Butte, and Central Tunnel (36), at the Comstock Lode, have been omitted. All mine

[7] Grout, F. F., "Behavior of Cold Acid Sulphate Solutions," ECON. GEOL., Vol. 8, 1913, No. 5.

waters are far from being saturated solutions; the average is about one hundredth normal.

TABLE II.

SHOWING PERCENTAGE OF RADICLES IN WATERS OF ACID, NEUTRAL AND ALKALINE REACTION.

	Fe.	Zn.	Cu.	Al.	Mn.	Na.	K.	Mg.	Ca.	SiO_2.	
Average per cent. in all acid waters...	6.0	5.6	3.6	1.7	0.7	1.0	0.7	2.0	8.9	2.6	22 acid waters with total solids averaging 2.96 grams per liter
Average per cent. in waters where present.....	6.2	6.5	5.3	1.9	1.1	1.2	1.0	2.0	8.9	2.6	
Number of waters in which present ...	21	19	15	20	16	18	16	22	22	22	
Average per cent. in all neutral waters	1.3	0.5	0.1	0.2	0.4	5.7	3.6	3.3	15.7	6.3	14 neutral waters with total solids averaging 0.82 grams per liter.
Average per cent. in waters where present.....	1.8	2.0	1.4	0.4	1.0	5.7	3.6	4.1	15.7	6.3	
Number of waters in which present....	10	3	1[1]	6	5	14	14	11	14	14	
Average per cent. in all alkaline waters	0.2	0.1	0.0	0.1	0.2	11.2	6.1	2.3	12.6	86	11 alkaline waters with total[2] solids averaging .66 grams per liter.
Average per cent. in waters where present.....	0.2	0.4	0.0	0.2	0.4	11.2	6.7	2.5	12.6	8.6	
Number of waters in which present....	10	3	1[1]	6	6	11	10	10	11	11	

1. Doubtful reaction.
2. Class D waters omitted.

If the percentages shown in Table II. are multiplied by the average total concentrations, the curves shown in Fig. 21 are obtained. These curves show that the actual concentration of all salts, excepting those of sodium and potassium, decrease as the solution changes from acid to neutral and from neutral to alkaline. Since salts of the heavy metals and of aluminum and manganese occur in large amounts in acid solutions, in small amounts in neutral, and are practically absent in alkaline solutions, they may, within certain limits, be used as indices of the reactions of the solutions in which they occur.

Probably all the acid waters of Class A were collected relatively near the surface, while the neutral or alkaline classes of waters from mines of sulphide ore deposits were found in the main at great depths. In some mines a decrease in acidity is shown by waters collected at successive depths. For instance the

Capote waters of the 300-foot level contain free H_2SO_4. At the Capote 900-foot level the waters contain no free acid. At Butte the Mountain View (1) and St. Lawrence (2) waters are acid, while the deeper waters of Gagnon (5), Glengarry (6), and Anaconda (7), are neutral or alkaline. At Homestake the two shallow waters are neutral and the deeper water is alkaline. All the very deep waters are neutral or alkaline, a fact which is illustrated by the Homestake 1,100 and 1,550-foot level water, the Green Mountain 2,200-foot level, Victoria Reef 4,280-foot level, and Gagnon 1,800-foot level.

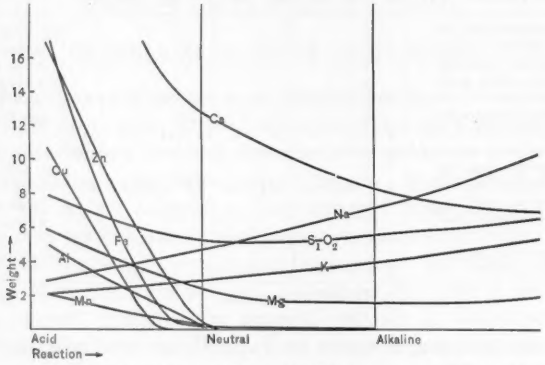

FIG. 21. Diagram showing weight of radicles in acid, neutral and alkaline waters.

As waters descend the concentration of salts of heavy metals decreases. At Capote the 300-foot level has 20 per cent. of the total salts in solution as sulphates of the heavy metals and at the 900-foot level only 12 per cent. are still present. At Ducktown the Burra Burra, at 100 feet, has 26 per cent.; the Callaway, at 127 feet, has 12 per cent. of heavy metallic sulphates. This same decrease is shown by the waters at Butte. In general, aluminum salts decrease with depth. For instance, the Burra Burra water collected above ground water level has 4.3 per cent. of $Al_2(SO_4)_3$, and the Callaway at 127 feet has 2.26 per cent. of

aluminum salts. On the other hand the alkalies increase with depth. Since the upper waters are acid and the deeper waters are neutral or alkaline, then the concentration of all the salts excepting those of sodium and potassium decrease with depth, a fact which is brought out by Fig. 21.

The change in the composition of the waters is also related to zones. At Capote the chalcocite zone ceases at the 900-foot level, as do also the copper salts in these deep waters. In the same mine the relative abundance of zinc salts increases below the chalcocite zone, showing that zinc salts are carried to much greater depths and are not precipitated so readily as the copper salts. At Ducktown the chalcocite zone is about 100 feet below the surface and below this level the waters show a decided decrease in copper salts. The enriched zone at Waihi-Tairua is at about 500–600 feet, and the waters collected below this level are free of copper salts.

In the Ducktown waters the total concentration decreases with depth. At Homestake the concentration increases downward to the 1,100-foot level and then begins to decrease, losing nearly half of its dissolved material in 500 feet. At Waihi-Tairua the deepest waters have the lowest concentration. If acidity decreases with depth in all mine waters, and if concentration decreases with acidity, then the concentration must decrease with depth.

If descending meteoric waters, as far as they have been observed, become less and less concentrated with metallic salts in depth, is it rational to assume that deep meteoric waters are agents of the formation of primary ore deposits under conditions that come under human observation?

In conclusion the writer wishes to express his thanks to W. H. Emmons, who suggested the problem and offered valuable suggestions in the course of the investigation.

COPPER DEPOSITS IN THE "RED BEDS" OF SOUTHWESTERN OKLAHOMA.[1]

A. E. FATH.

INTRODUCTION.

The copper deposits occurring in "Red Beds" have a peculiar interest for geologists, not because of their economic importance, but because of the obscurity surrounding the problem of the source of the copper and the manner in which it is deposited. Many articles[2] describing these deposits have been written, but up to the present time no one has reported that the copper is a replacement of an older sulphide mineral as is the case with the deposits found in southeastern Cotton County, Oklahoma, which the observations recorded in the following pages seem to show.

[1] Published with the permission of the Director of the U. S. Geological Survey.

[2] The more important of these are:

Beck, Dr. R., and Weed, Walter H., "The Nature of Ore Deposits," New York, 1905, pp. 497–504.

Emmons, S. F., "Copper in the Red Beds of the Colorado Plateau Region," U. S. Geol. Survey Bull. 260, pp. 221–232, 1905.

Emmons, W. H., "The Cashin Mine, Montrose County, Colo.," U. S. Geol. Survey Bull. 285, pp. 125–128, 1906.

Gale, H. S., "Geology of the Copper Deposits near Montpelier, Bear Lake County, Idaho," U. S. Geol. Survey Bull. 430, pp. 112–121, 1909.

Lindgren, Waldemar, "Mineral Deposits," New York, pp. 369–376.

Lindgren, Waldemar, "Notes on Copper Deposits in Chaffee, Fremont, and Jefferson Counties, Colorado," U. S. Geol. Survey Bull. 340, pp. 170–174, 1908.

Lindgren, Waldemar, Graton, L. C., and Gordon, C. H., "The Ore Deposits of New Mexico," U. S. Geol. Survey Prof. Paper 68, pp. 48, 76–79, 143–149, 163, 202–203, 1910.

Schmitz, E. J., "Copper Ores in the Permian of Texas," *Trans. Am. Inst. Min. Eng.*, vol. 26, pp. 97–108, 1896.

Stelzner, Alfred Wilhelm, and Bergeat, Dr. Alfred, "Die Erzlagerstätten," pp. 388–439, 1904. An excellent bibliography for European occurrences is given.

Tarr, W. A., "Copper in the 'Red Beds' of Oklahoma," ECONOMIC GEOLOGY, vol. 5, pp. 221–226, 1910

The generally accepted conclusion concerning the manner in which the "Red Beds" copper was deposited is briefly summarized by Emmons in the following words:

"Although these deposits are not secondary in the sense that they have formed at the expense of older sulphides, the conditions under which they were formed as regards temperature, pressure, and concentration of solution are probably near those which prevail in processes of sulphide enrichment."[3]

Geography, Topography, and Geology.—The material for the present study was collected in the summer of 1913 during an examination of prospective oil territory in southeastern Cotton County just north of Red River which here forms the boundary line between Texas and Oklahoma. The area is a gently undulating plain trenched by a few shallow stream valleys. The total amount of relief is about 200 feet.

Rock exposures are comparatively rare, being confined to localities of rapid erosion along streams and on steep slopes. The surface rocks belong to the Wichita formation, the lowest division of the Permian in this general region. They consist of beds of red shales 15 to 30 feet thick which alternate with red or white sandstone beds whose average thickness is 10 to 15 feet. The shales contain, at a few places, dark colored beds in which carbonaceous matter is abundant, and a few thin lentils of coal, in places about an inch in thickness, which appear to have been formed from single logs. It is in association with these carbonaceous deposits that one form of the copper is usually found.[4]

[3] Emmons, W. H., "The Enrichment of Sulphide Ores," U. S. Geol. Survey Bull. 529, pp. 107–108, 1913.

[4] For a more detailed description of the Wichita formation of this general region, the reader is referred to the following reports:

Munn, M. J., "Reconnaissance of the Grandfield District, Oklahoma," U. S. Geol. Survey Bull. 547, 1914.

Gordon, C. H., "Geology and Underground Waters of the Wichita Region, North Central Texas," U. S. Geol. Survey Water Supply Paper 317, 1913.

Udden, J. A., and Phillips, D. McN., "A Reconnaissance Report on the Geology of the Oil and Gas Fields of Wichita and Clay Counties, Texas," Univ. of Texas Bull. 246, 1912.

Wegemann, Carroll H., "Geology and Oil Resources of Southeast Cotton and Southwest Jefferson Counties, Oklahoma," U. S. Geol. Survey Bull. 602, (in press).

COPPER DEPOSITS.

The copper deposits of this region, like most of those associated with the "Red Beds" of other regions, are not of commercial importance. The deposits are found in both sandstone and shale, and the various forms in which they occur are as follows: (a) Nodules in sandstone; (b) finely disseminated malachite in sandstone; (c) surface stains on sandstone; (d) nodules in shale; (e) cuprified wood. The last two occurrences noted are the most important in the present study since they are the only ones which present new evidence on the subject of copper deposition.

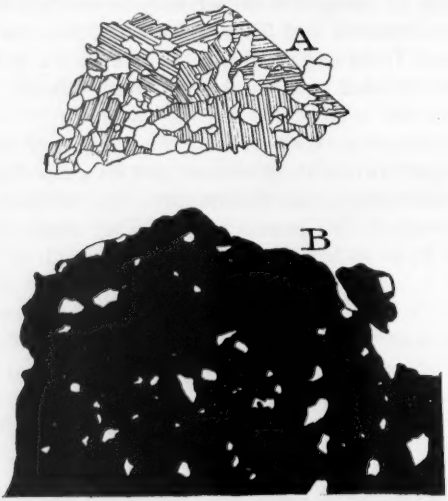

FIG. 22. Microdrawing of thin section of chalcocite nodule and adjoining sandstone. Outlined with camera lucida. A. Sandstone composed of quartz grains cemented by crystalline calcite. B. Chalcocite nodule bearing quartz grains which are more widely separated than in the adjoining sandstone. A. Enlarged 24 diameters.

(*a*) *Nodules in Sandstone.*—These were found at only two outcrops in the region, one of which is in the SW¼ SE¼ Sec. 35, T. 4 S., R. 10 W. They are conspicuous because of their green carbonate surfaces which are an alteration of the chalcocite

interiors. Embedded in the chalcocite are many sand grains which are more widely separated than in the adjoining sandstone (Fig. 22), a condition which seemingly indicates that during the growth of the nodule by a replacement of the calcite cement, the sand grains tend to be excluded. The replacement of the calcite by chalcocite is not direct, as will be explained on a later page.

(*b*) *Finely Disseminated Malachite in Sandstone.*—Sandstones carrying copper in this form were rare. They show a decided greenish tinge on fresh faces, but the weathered surfaces are usually too highly discolored by manganese oxides and other weathering products to show the presence of copper. The malachite, where found, comprises but a small part of the cement of the sandstone, and is probably a metasomatic replacement of the calcite which forms the greater part of the cementing material. Such a replacement takes place under oxidizing conditions.[5] In specimens showing this type of copper deposit, a small part of the cement is composed of manganese oxides which are segregated at certain points in the rock, giving to the freshly broken surface a spotted appearance. Around these spots there appears to be greater concentration of the malachite. Whether or not the two minerals are of contemporaneous origin is not known.

(*c*) *Surface Stains on Sandstone.*—Here and there in the region the sandstone outcrops carry surface stains of malachite which probably is being precipitated from ground waters by evaporation at the present time.

(*d*) *Nodules in Shale.*—These nodules, conspicuous because of their green and blue carbonate surfaces, are usually found where the embedding clay has been removed, leaving them as residual material on the surface of the ground. They occur both as simple and compound forms. The simple forms range from subspherical to irregular masses, of which none are larger than a hickory-nut, and the compound forms are intergrown aggregates of the simple forms.[6]

[5] Emmons, W. H., "The Enrichment of Sulphide Ores," U. S. Geol. Survey Bull. 529, p. 96, 1913.

[6] Similar nodules are illustrated in Plate XVIII., Univ. Texas Bull. 246, "A Reconnaissance Report on the Geology of the Oil and Gas Fields of Wichita and Clay Counties, Texas," by J. A. Udden and D. McN. Phillips, 1912.

The interior of these nodules show, within the outer rim of malachite and azurite, a dark material which is largely chalcocite. A hand lens may bring out a few minute brassy patches of iron sulphide, probably marcasite,[7] but only by the examination of a polished face of the nodule with a metallographic microscope is the disseminated character of this mineral clearly shown (Fig. 23).

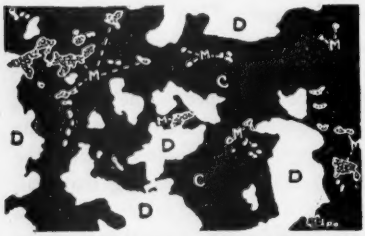

FIG. 23.

FIG. 24.

FIG. 23. Microdrawing of polished surface of cupriferous nodule from shale. Outlined with camera lucida. Shows remnants of marcasite (M) embedded in chalcocite (C). The large white areas (D) are depressions filled with material used in polishing. Enlarged 105 diameters.

FIG. 24. Photograph of a cupriferous nodule from shale. Shows star shaped cavity in the interior. Same nodule as in Fig. 23. Enlarged 3 diameters.

The marcasite is usually completely inclosed by massive chalcocite. Near the outer margin is a zone in which marcasite is more abundant than nearer the center. The reason for this is not clear. Here and there in the chalcocite are minute patches of malachite, probably following fracture planes. One of the nod-

[7] This determination is not certain. The freshly cleaned surface of the mineral is a pale brass-yellow which resembles more nearly the common color of marcasite rather than pyrite. Its presence in sedimentay rocks as a nodule formed by precipitation from cold meteoric waters would also seem to favor the probability of its being marcasite. The amount of material available from the specimens collected seemed insufficient for making the chemical determinations described by H. N. Stokes in U. S. Geol. Survey Bull. 186, "On Pyrite and Marcasite," and some preliminary tests by the method described by Dr. Max Leo in "Die Anlauffarben, eine neue Methode zur untersuchung opaker Erze und Erzgemenge," Dresden, 1913, gave no satisfactory results.

ules in the collection has in its center a cavity, star-shaped in cross-section (Fig. 23), which is partly filled with crystalline malachite. The discussion of these phenomena will be taken up later.

Similar nodules occur near Trautenau, Bohemia, and are described by Stelzner and Bergeat as "Konkretionen, die innen aus Kupferglanz, ausen aus Pyrit bestehen."[8] Beck and Weed mention concretions as occurring at Wernersdorf near Radowenz, Bohemia, which "are often as large as the palm of the hand, containing copper glance inside, which gradually passes over into pyrite."[9] Copper nodules are reported to occur near New Annan, Nova Scotia. Henry Louis describes them as follows: "They consist of very pure chalcocite, but I also found some of covelline, more or less pure, and of other indeterminate copper minerals, possibly all alteration products of chalcocite and chalcopyrite. All the nodules were coated with carbonate of copper, which had also filled up any cracks in the nodules, and had impregnated the sandstone bed to a certain extent."[10] In neither of these cases is the relation of the chalcocite to the pyrite discussed.

(*e*) *Cuprified Wood.*—In the north bank of Red River in Secs. 2 and 3, T. 5 S., R. 11 W., about 1½ miles south of Taylor, there are found at several places, in close relation with thin carbonaceous beds, specimens which at first appeared to be highly carbonized wood. The coaly material is merely a film covering a dark-blue and green surface of azurite and malachite, which in turn is the oxidized margin of the chalcocitized interior. A polished face of this interior also shows, in a manner similar to the nodules, the presence of marcasite (Figs. 25 and 26). This marcasite is present in patches ranging from microscopic sizes up to masses a centimeter in cross-section.

Similar occurrences are reported by Henry Louis to be near New Annan, Nova Scotia, at which place there is a nodule bed

[8] Stelzner, Alfred Wilhelm, and Bergeat, Dr. Alfred, "Die Erzlagerstätten," p. 390, 1904.

[9] Beck, Dr. R., and Weed, Walter H., "The Nature of Ore Deposits," New York, p. 497, 1905.

[10] Louis, Henry, discussion of paper by Mr. E. J. Schmitz, *Trans. Am. Inst. Min. Eng.*, vol. 26, p. 1052, 1896.

of Permian age which contains "obscure plant remains converted into anthracite, chalcopyrite, chalcocite, and iron pyrites."[11] In this case, the relation of the minerals is also not discussed.

EVIDENCE FOR SECONDARY NATURE OF THE COPPER PRESENTED BY THE NODULES IN SHALE AND THE CUPRIFIED WOOD.

Even without microscopic examination it is evident that in both the fossil wood and the nodules the chalcocite commonly surrounds the marcasite and with the microscope complete gradations

FIG. 25.

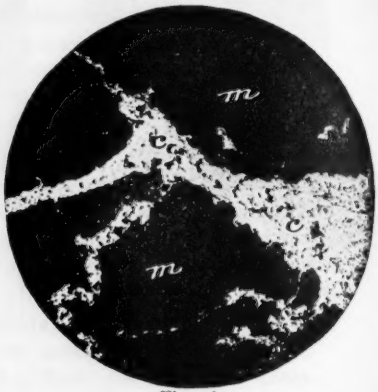

Fig. 26.

FIG. 25. Photomicrograph of polished surface of cuprified wood. Shows distribution of marcasite (m) and chalcocite (c) with relation to the preserved cellular texture of the wood. Enlarged 40 diameters.

FIG. 26. Photomicrograph of polished surface of cuprified wood. Shows replacement veinlet of chalcocite (c) in marcasite (m). Enlarged 20 diameters.

are traceable from pure chalcocite through an intricate association of the two minerals into pure marcasite. Such relationships at once suggest that the one mineral may be a replacement of the other, and detailed study fully confirms this suggestion, for it shows that in specimens of the fossil wood marcasite is traversed

[11] Louis, Henry, discussion of paper by Mr. E. J. Schmitz, *Trans. Am. Inst. Min. Eng.*, vol. 26, pp. 1051–1052, 1896.

by replacement veinlets of chalcocite. These veinlets, which are illustrated in Fig 26, do not show the characteristics of simple filled fissures, the opposite sides of which would match if brought together, but on the contrary have forms indicative of replacement, the opposite sides showing little or no similarity to each other in form.

Further argument for the replacement origin of the chalcocite may be found in the fact that no instances are on record of the formation of chalcocite concretions whereas marcasite concretions, as is well known, are extremely common. Furthermore, it seems improbable that these two minerals so widely different in chemical characteristics should have been deposited simultaneously under the same chemical and physical conditions.

From these considerations, it seems necessary to conclude that the nodules were originally concretionary growths of marcasite, and it seems plausible to conclude that the wood was originally fossilized by marcasite. The chemistry of such replacements is the same as for secondary sulphide enrichment and need not be discussed in this paper. The probable sulphide replacement or secondary nature of the chalcocite of these deposits is the way in which they differ markedly from those described by Tarr,[12] Lindgren,[13] S. F. Emmons,[14] W. H. Emmons,[15] Lindgren, Graton and Gordon[16] and others.

OTHER FEATURES PRESENTED BY THE NODULES IN SHALE AND CUPRIFIED WOOD.

Cavity in Nodule.—Several other features that should be mentioned are presented by the sections of the nodule and the fossil

[12] Tarr, W. A., "Copper in the 'Red Beds' of Oklahoma," ECONOMIC GEOLOGY, vol. 5, pp. 221–226, 1910.

[13] Lindgren, Waldemar, "Notes on Copper Deposits in Chaffee, Fremont, and Jefferson Counties, Colorado," U. S. Geol. Survey Bull. 340, pp. 170–174, 1908.

[14] Emmons, S. F., "Copper in the Red Beds of the Colorado Plateau Region," U. S. Geol. Survey Bull. 260, pp. 221–232, 1905.

[15] Emmons, W. H., "The Cashin Mine, Montrose County, Colorado," U. S. Geol. Survey Bull. 285, pp. 125–128, 1906.

[16] Lindgren, Waldemar, Graton, L. C., and Gordon, C. H., "The Ore Deposits of New Mexico," U. S. Geol. Survey Prof. Paper 68, 1910.

wood. The star-shaped cavity in the nodule (Fig. 24) raises the question whether this cavity was formed in the pre-existing marcasite concretion or since the replacement by chalcocite. No new evidence for the cause of the internal fissuring of concretions is indicated. Todd[17] has ably discussed this phenomenon. He explains it as due to charged solutions entering a concretion and depositing more material in a zone near the outside than in the center. This zonal addition of material induces circumferential tension which causes the interiors to fissure. Such an explanation would indicate the cavity to have been formed during the segregation of the marcasite. In this particular instance the replacement of the marcasite was truly metasomatic, the chalcocite being deposited only where a particle of marcasite was removed, and thus the internal cavity was preserved. The vuggy malachite now present in this cavity is probably due to the action of later carbonate waters altering the chalcocite in the interior in the same manner in which they have affected the exterior of the nodule.

Preservation of Wood Cell Texture.—An interesting feature illustrated by the polished section shown in Fig. 25 is a marked preservation in the fossil wood, of cellular texture which endured through the marcasitizing stage and is now revealed in the chalcocite. In the unaltered marcasitized portion of the wood no cellular texture is discernible. This does not mean that films of carbonaceous or other material which outline the cells are absent in the marcasite, but simply that they are not revealed, because the marcasite is not subject to as highly a polished surface as the chalcocite. The marcasite in the fossil wood takes a polish much less readily than the marcasite of the nodules or pyrite from metalliferous lodes, a condition which is probably caused by the presence of the minute cellular texture making the material less coherent than the more massive form.

Influence of Wood Structure in Replacement.—Fig. 25 also shows how the wood structure has influenced chalcocitization. The more easily penetrated channels along the grain of the wood are preserved more or less in the marcasitized wood, for chalco-

[17] Todd, J. E., "Concretions and their Geological Effects," *Bull. Geol. Soc. America*, vol. 14, pp. 353–368.

citization has progressed more readily along the grain than across it.

A detail not shown in Fig. 25 and which is only dimly discernible upon high magnification of the specimen with the microscope is found in a few of the ringlike cellular areas of the fossilized wood where a faint brassy appearance is present, while the surrounding material, both inside and out, is clearly chalcocite. Evidently the marcasite within these areas is the last to be replaced. This is illustrated in Fig. 27.

Association of Barite with Copper.—Associated with "Red Beds" copper ores, Lindgren[18] and Emmons[19] report barite as

FIG. 27. Microdrawing of polished cross-section of preserved cell in cuprified wood. The cell wall contains scattered particles of marcasite (m) and is both filled and surrounded by chalcocite (c). Enlarged 425 diameters.

occurring in the deposits of Fremont County and at the Cashin mine in Montrose County, Colorado. Barite is also mentioned as present at two places in New Mexico.[20] No barite was found in the area examined in southwestern Oklahoma, but D. F. Hewett of the United States Geological Survey has found it in nodular form weathered out of the red shales at several places in this general region, one mile south and three miles north of Electra, Texas, and three miles east of Grandfield, Oklahoma.[21]

[18] Lindgren, Waldemar, "Notes on Copper Deposits in Chaffee, Fremont, and Jefferson Counties, Colorado," U. S. Geol. Survey Bull. 340, pp. 170–174, 1908.

[19] Emmons, W. H., "The Cashin Mine, Montrose County, Colorado," U. S. Geol. Survey Bull. 285, pp. 125–128, 1906.

[20] Lindgren, Waldemar, Graton, L. C., and Gordon, C. H., "The Ore Deposits of New Mexico," U. S. Geol. Survey Prof. Paper 68, p. 77, 1910.

[21] Oral communication.

SUMMARY.

The copper deposits in the "Red Beds" of Cotton County, Oklahoma, are similar to other "Red Beds" copper deposits in the occurrence of the copper minerals as nodules and as replacements of carbonaceous material and in their low percentage of copper, below the present economic limit. Their special interest lies in the fact that the copper is probably a replacement of an earlier sulphide mineral and that its precipitation follows the general rule laid down for secondary sulphide enrichment. It is to be regretted that unaltered marcasite concretions and marcasitized wood, which probably are present at considerable depth, could not be obtained because of the absence of mines or other means for collecting them. Whether similar sulphide replacements occur in "Red Beds" copper deposits elsewhere is not known, but it seems probable that it has taken place in the deposits previously mentioned near Trautenau and Wernersdorf, Bohemia and New Annan, Nova Scotia. Closer observation and further collection of material may, perhaps, show the phenomena to be more prevalent than is known at present. No evidence pertaining to the source of the copper was found in the region examined.

In conclusion, the writer wishes to express his appreciation to Mr. Carroll H. Wegemann, to whom he was an assistant during the work in southwestern Oklahoma, for the use of the material collected and for the helpful interest shown during the present investigation. He also wishes to express his thanks to Dr. Edson S. Bastin for several valuable suggestions and helpful assistance, and to Dr. Adolph Knopf for a critical reading of the paper.

ON TEMPERATURES THAT OBTAIN IN ZONES OF CHALCOCITIZATION.

W. H. Emmons.[1]

INTRODUCTION.

Introduction.—The conditions that obtain in the zones where secondary or superficial processes operate in deposits of sulphide ores are near those that may easily be duplicated in the chemical laboratory. These zones are generally within 1,000 feet of the surface and very rarely are these processes operative as much as 2,000 feet in depth. When sulphide enrichment takes place at considerable depths below the water level the pressures are equivalent to several atmospheres; but the data that are accumulating on the effect of pressure on chemical reactions show that this factor is subordinate compared to temperature, at least within the range of moderate pressures such as obtain in zones of secondary sulphide enrichment. Nearly all of the experiments that have been made to illustrate processes of sulphide enrichment have been carried out at room temperatures and under atmospheric pressures. Many of them have served greatly to elucidate the natural processes and under conditions that may with great probability be assumed to approximate closely, though not exactly, those that obtain in zones where the natural processes are operative. But one of these series of reactions, the substitution of pyrite by copper sulphide, has offered puzzling difficulties. This synthesis was first accomplished by H. V. Winchell[2] and later by T. T. Read.[3]

[1] Published by permission of the Director of the United States Geological Survey.

[2] Winchell, H. V., "Synthesis of Chalcocite and Its Genesis at Butte," *Bull. Geol. Soc. America*, vol. 14, pp. 269–276. Tolman, C. F., "Secondary Sulphide Enrichment," *Min. and Sci. Press*, vol. 106, pp. 38–43, 141–145, 178–181.

[3] Read, Thomas T., "The Secondary Enrichment of Copper-Iron Sulphides," *Trans. Am. Inst. Min. Eng.*, vol. 17, 1906, pp. 297–303, and 895.

In their experiments copper sulphate was brought in contact with pyrite in the presence of SO_2 and the pyrite was covered with a chalcocite film. It is not certain, however, that these experiments ideally represent the natural processes, for SO_2 has never been determined in any mine water, although it has been looked for, particularly in waters from Ducktown, Tenn., and Creede, Colo., and perhaps in other waters. In experiments designed to illustrate processes of sulphide enrichment for several years past my associates and I have attempted this synthesis without introducing SO_2 under many and varied conditions, but all of our experiments have been without success. In one series of experiments Mr. F. F. Grout has had finely ground pyrite at room temperature in contact with a solution of $n/10$ H_2SO_4 and $n/10$ $CuSO_4$ nearly two years without precipitation. In another series with these salts and $n/10$ $FeSO_4$ the pyrite is still untarnished. In a series of experiments carried out in connection with studies of sulphide enrichment of the copper deposits at Ducktown, Tenn.,[4] Dr. R. C. Wells found that a dilute acid solution (0.057 n H_2SO_4) at room temperature will attack pyrrhotite, galena and sphalerite and liberate hydrogen sulphide. But such a solution does not attack pyrite and chalcopyrite vigorously, if at all. The amounts of H_2S indicated in the solutions that had been in contact with pyrite and chalcopyrite were so small that Dr. Wells considered them to represent possibly a correction for the end point of titration. No H_2S could be shown to have been generated by pyrite and chalcopyrite by using lead acetate paper,—an exceedingly delicate test. The importance of the relations shown by the series of experiments cited above is obvious, for copper sulphide, even from dilute solutions of copper sulphate is precipitated instantaneously by hydrogen sulphide, and any reaction that yields hydrogen sulphide, reasonably may be invoked to illustrate the processes that form chalcocite from pyrite in the presence of $CuSO_4$.

A paper recently issued by John Dustin Clark[5] describes an

[4] Emmons, W. H., "The Enrichment of Sulphides Ores," U. S. Geol. Survey Bull. No. 529, 1912, p. 59.

[5] Clark, John Dustin, "A Chemical Study of the Enrichment of Copper Sulphide Ores." Bulletin, University of New Mexico, whole number 75, Chemistry series, vol. 1, No. 2, 1914, pp. 80–150.

extensive series of experiments that has been performed to illustrate processes of enrichment of copper sulphide ore. In one of these experiments (No. 23, p. 116), duplicate tubes containing 15 c.c. of *N*/10 sulphuric acid with 0.5 gram 200-mesh pyrite were sealed and kept constant at about 41°. After 51 days appreciable H_2S was shown in the solution. Similar experiments with chalcopyrite and bornite were accomplished and in all H_2S was generated, but pyrite set free more H_2S than chalcopyrite, and bornite less H_2S than chalcopyrite.

Room temperatures are about 18° C. It is noteworthy that by raising the temperature of the solution to 41° Clark has obtained H_2S from pyrite with acid in 51 days, whereas my associates and I have not been able at 18° to generate H_2S from pyrite with acid and with acid and iron sulphate in several states of oxidation through periods of nearly two years. The range of temperature—even the narrow range from 18° to 41°—is obviously important in these experiments assuming of course that the material used in them was pure.

Factors Considered in Estimating Temperature of Chalcocitization.—Many factors are to be considered in estimating the temperature of solutions in zones where chalcocitization is operative. Of these the most important are, (1) the mean temperature at the surface and the temperature range, (2) the downward increment of temperature in the earth's crust, (3) the increase of temperature of the solution due to oxidation of pyrite and other minerals that are unstable in the presence of air and water.

Temperatures at Surface.—From data supplied by reports of the chiefs of the Weather Bureau I have calculated the average mean annual temperature at Globe, Bisbee, and Butte.

Place.	Globe.	Bisbee.	Butte.
1895	62.2[5a]	60.4	40.
1907	62.8	59.2	42.2
1908	62.4	58.8	43.4
Aver. Fahr.	62.5 F.	59.5 F.	41.9 F.
Centigrade	17.0 C.	15.3 C.	5.5 C.

[5a] Globe for 1902–1903, all data from reports of the chiefs of the Weather Bureau, U. S. Dept. of Agriculture.

It is generally assumed that at a depth of about 50 feet the temperature of rocks is approximately the average mean annual temperature of the place. Below that depth the temperature increases steadily downward. But solutions moving downward even sluggishly will probably carry heat below the depth of constant temperature of rocks, and it is not improbable that the solutions are affected by seasonal variations to depths far below 50 feet.

Earth's Increment of Heat.—The increase of temperature from the surface of the earth downward is variable. Much data on this subject has been collected by the Committee on Underground Temperatures of the British Association for the Advancement of Science, and published in their reports from year to year. The increment ranges from 1° F. in less than 20 feet to 1° F. in 130 feet, with an average of 1° F. in 50 to 60 feet.[6] In the deeper holes measured in recent years the average increment is below rather than above 1° F. in 60 feet.

It is hardly necessary to call attention to the fact that these measurements, at least the deeper ones, were made in bore holes, tunnels, and mines of native metal ores, and that many measurements were in dry rocks. The rocks therefore have not been heated by oxidizing sulphide or by other oxidizing reactions to any appreciable extent. We may assume with considerable confidence then that the normal increment of heat of the earth from the surface downward is not far from 1° C. for 100 feet.

Below the surface, the earth's heat probably warms the rocks about 1° C. for every hundred feet in depth. But the temperature of the rocks underground is not necessarily the temperature of the solutions. Oxidation of sulphides raises the temperature of the solutions to points above the normal heat of the rocks, and below the zone of oxidation the solutions may be hotter than the rocks, for they are moving downward and carrying heat downward from the oxidizing zone. They will probably not lose much heat to the rocks, however, because the conductivity of rocks is exceedingly low, and after the rocks have been warmed by the solu-

[6] Chamberlin, T. C., and Salisbury, R. D., "Geology," vol. I., Processes, second edition revised, 1909, pp. 569.

tions in the near vicinity of the deposits, but little heat should be lost, and in our calculation we are probably justified in ignoring it for the present. We cannot invoke this as an important permanent source of heat to raise the temperature of solutions moving downward even sluggishly, for the solutions would soon carry any excess heat away from its path, and as already stated, the conductivity of rocks is so low that the transfer of heat is exceedingly slow. Where the water descending in an ore deposit mingles with water from outside sources, it is doubtless cooled. The importance of this factor will obviously depend on local structures.

Heat Due to Oxidation.—The heat due to oxidation is a factor that can only be approximated. Let us assume a pyritic copper deposit in which solutions are moving downward from the oxidizing zone, and where there is little contamination by waters outside the deposits. Such conditions might be expected in the great bodies of disseminated copper ores or in fissure veins strongly fractured after deposition and inclosed in rocks that are relatively impervious. Let it be assumed that the concentration and composition of the waters are as shown in the following table, which is the average of analyses of 42 mine waters obtained from deposits of sulphide ores.

It is evident that the salts of such a solution have formed by the oxidation of sulphides, for over 75 per cent. of the total salts is SO_4. The SO_4 has formed mainly from the oxidation of pyrite. Later it combined with alkalies, alkaline earths, and other radicals to form sulphates of those metals. Since pyrite so greatly exceeds other sulphides in many copper deposits, we may for the time being assume that all of the sulphate is from pyrite, and since few sulphates are permanently soluble, for the present we may leave out of consideration the sulphates precipitated from the solutions. But we cannot ignore the ferric iron that is left in the gossan, for its oxidation, as well as that of sulphur must be an important source of heat, and this heat is carried downward by the solutions.

[7] Emmons, W. H., and Harrington, G. L., "A Comparison of Waters of Mines and of Hot Springs," ECONOMIC GEOLOGY, vol. VIII., p. 653, 1913.

AVERAGES OF FORTY-TWO ANALYSES OF MINE WATERS.

	1.	2.
Cl	39.30	.40
Br	tr.	
I	—	
F	tr.	
SO_4	7,551.99	75.89
CO_3	83.01	.83
PO_4	tr.	tr.
AsO_4	tr.	tr.
B_4O_7	tr.	tr.
NO_3	tr.	tr.
S	.02	tr.
As	—	—
Sb	—	—
Na	63.28	.64
K	30.32	.31
Li	—	
NH_4	—	
Ca	161.01	1.62
Sr	—	
Ba	—	
Mg	171.16	1.72
Mn	40.76	.41
Fe	239.70	2.41
Al	253.97	2.55
Co, Cd, Ni, Pb	1.22	.01
Cu	1,147.69	11.53
Zn	53.14	.53
SiO_2	53.07	.53
SiO_3	—	—
H	61.31	.62
Totals	9,950.93	100.0

1. Results expressed as parts per million.
2. Results expressed as percentages of dissolved material.

On the heat generated by oxidation of pyrite there is some difference of opinion, this complex molecule offering more difficulties in experimental work than any of the other common minerals. E. E. Somermeier[8] determined the calorific value of pure pyrite

[8] Somermeier, E. E., "Forms in which Sulphur Occurs in Coal, Their Calorific Values and Their Effects on the Accuracy of the Heating Powers Calculated by Delong's Formula," *Jour. of the Amer. Chem. Soc.*, vol. XXVI., 1904, p. 555.

by burning it directly in a calorimeter with coal of known heat value. He obtained in several series results corresponding closely and made corrections for minute quantities of unoxidized products remaining in the calorimeter. The average of two series of experiments is 2,637 calories per gram of pyrite. The oxidation products are $Fe_3O_4 + 6SO_3Aq$.

The iron in 1 gram pyrite equals .466 grams and can be oxidized to .644 grams magnetite.[9]

In the solution 7,551.99 parts of SO_4 in a million correspond to 2517.33 parts of sulphur. Since pyrite carries 53.4 sulphur, 4714 parts of pyrite would be required to oxidize to give a water carrying 7,551.99 parts of SO_4 per million. On oxidation 4,714 grams of pyrite would yield 4714×2700 or 12,727,800 calories. A calorie is the quantity of heat required to raise one gram water one degree in temperature between 0° and 100° centegrade. The amount of heat required depends somewhat upon the temperature of the body, that is, it does not require exactly the same amount of heat to raise a body from 10° to 11° as from 50° to 51°, but the differences are so small in the range between 0° and 50° that here they may be disregarded. A million grams of water by oxidation of 4,714 grams pyrite to ferric oxide and sulphuric acid will be warmed thereby about 12.7° C.; and the heat of oxidation of an ore body yielding a water carrying 7,551.99 parts SO_4 in a million will raise the temperature of that water about 12.7°. It matters little whether the downward moving oxidizing solution moves slowly or rapidly. If it moves slowly, there is a longer time for it to react with pyrite; if it moves rapidly, oxidation must be more vigorous to yield a solution like that assumed. But the amount of oxidation and therefore the heat generated per unit

[9] 1 gram of iron oxidized to Fe_3O_4 gives 1,612 calories.

1 gram of iron oxidized to Fe_2O_3 gives 1,746 calories.

1 gram of iron in magnetite oxidized to Fe_2O_3 gives 134 calories, and .466 gram of iron will give more heat (62.4 calories) when oxidized to Fe_2O_3 than when oxidized to Fe_3O_4. We may assume then that a gram of pyrite oxidized to ferric oxide and to sulphuric acid will give $2,637 + 63$ or 2,700 calories.

Peters, E. D., "The Principles of Copper Smelting," Hill Pub. Co., N. Y., 1907, p. 531. This method may not be precisely accurate, but is sufficiently so for purposes of this calculation, where at best the result can be only a probable estimate.

volume of water are the same. If, however, the solution is nearly stagnant, there would be more loss of heat in the vadose zone. In this zone, air is present in openings in rocks, and its circulation, though probably exceedingly slow, cannot wholly be disregarded. Moreover, rocks, though very poor conductors of heat, if given time enough would carry appreciable heat away from the solution.

The mingling of cold solutions that do not carry SO_4 with the sulphate solution would not greatly affect the results of this calculation. Such solutions would have lowered the temperature of the sulphate water, but they would also have diluted it, and the calculations are then on the basis of the diluted solution. If we assume that the water has been diluted and cooled by other waters, we must assume that it was formerly more highly concentrated and therefore more heated.

General Discussion.—I have presented above an ideal case, and have shown that the oxidation of enough pyrite to yield a water carrying the same amount of sulphate radical that is shown in the average of 42 analyses of mine water will raise the temperature of that water about 12.7°. It is possible that the concentration is too high, for two of the 42 analyses of mine water carry abnormal amounts of SO_4. More probably, it is too low, for most of the waters analyzed were taken from open mines where circulation had been stimulated by providing artificial channels. Analyses of waters in mines of sulphide ores taken before an artificial circulation is established would throw much light on this point.

We have not taken into account any conduction of heat through the rocks, but this, as stated above, is certainly small, because rocks are poor conductors of heat. There are, moreover, certain other sources of heat that should be considered. Some sulphates are relatively stable, and after oxidation remain in the gossan. Their formation is attended by production of heat, yet the oxidation products do not go permanently in solution, and for that reason we have not taken account of them thus far. Of these products anglesite and secondary barite are most important, although neither is abundant in most copper deposits. The fuel value of lead sulphide, which is converted to lead sulphate, is low

(817 calories per gram of PbS). We can probably disregard basic ferric sulphates and iron, copper and zinc sulphates, for these, though fairly stable, ultimately go into solution, and then the sulphate radical is carried downward, and therefore it has been considered in our calculations. Basic copper sulphates are fairly stable in the oxidizing zone, but generally they are not abundant.

Zinc is present, and its fuel value should be considered. A gram of sphalerite oxidized to zinc sulphate gives 1,922 calories. Although its fuel value is lower, its sulphur value is only 62 per cent.[10] of that of pyrite. Oxidation of a mass of ZnS that contains 1 gram of sulphur will yield about 5824 calories, whereas the oxidation of a mass of pyrite that carries 1 gram sulphur will yield 5056 calories. Thus, if two solutions are formed, one from the oxidation of pyrite, and one from the oxidation of sphalerite, both these solutions carrying the same amount of SO_4, the one made from zinc blend will be attended by the production of a little more heat than the one made from pyrite, but the difference is small.[11]

One other source of heat should be mentioned, and that is the reaction of the solution on the wall rock. Where acid attacks calcite, heat is produced. Richards says the reaction $CaCO_3 + SO_3 = CaSO_4 + CO_2$ gives 871 calories per gram of lime.[12] This source of heat is obviously small, even if all of the acid should be used up to form lime sulphate. I have no data on the heat evolved where acid attacks feldspars to form kaolin, but the reaction probably gives off a little heat.

Summary.—Nearly all these data seem to point in one direction —that the estimate of heat generated by oxidation of pyritic copper deposits is somewhat above rather than below the amount necessary to raise the average mine water 12.7° C. If the solution starts moving downward with an initial temperature of 17° (which

[10] See a chapter on Thermo Chemistry by J. W. Richards, in "Principles of Copper Smelting," by E. D. Peters, New York, 1907, p. 530.

[11] Except for pyrite, these figures probably do not take into account heat of solution, which is small and would not alter the results appreciably.

[12] *Loc. cit.*, p. 543.

is the mean annual temperature at Globe) we can assume the temperature that prevails where chalcocitization takes place to be about 30° or perhaps a little more. In summer months, June 1 to September 30, temperatures are higher at Globe. The average is 25.5° (average for 1902, 1907, 1908). If seasonal variations are assumed to affect the solutions, as they may where downward circulation is rapid, the temperature, in summer months, initially 25.5°, when raised 12.7° by oxidation, would be about 38.2°.

The fact that the temperatures of the reactions in the lower portion of deposits undergoing superficial alteration, are even slightly above room temperature[13] seems to me a matter of some importance, and one that cannot be ignored in a discussion of the reactions assumed to take place in processes of sulphide enrichment, for, as Clark[14] has shown, pyrite with $N/10$ H_2SO_4 will generate H_2S at 41° C. whereas the reaction at room temperature takes place, if at all, so slowly that it is not appreciable in two years.

[13] Average for summer months at Globe, 1902, is 78.1° F.; 1907 is 77.7° F.; 1908 is 78.1° F.

[14] Clark, John Dustin, *loc. cit.*, p. 116.

THE PITCHBLENDE OF CORNWALL, ENGLAND.

R. A. F. Penrose, Jr.

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Pitchblende has long been a well-known mineral, but has attracted a greatly increased interest since it became important as a source of radium. Among other localities, it occurs in many places in Cornwall, England, and though the writer is not so familiar with its occurrence there as he would wish, yet as only very brief accounts of it have been published, he ventures to offer the following article.[1] The material for the present paper is derived partly from a personal examination of some of the Cornish mines several years ago, partly from brief descriptions in the published literature on the region, and partly from information from persons who have recently sought pitchblende in Cornwall.

USES OF PITCHBLENDE.

Pitchblende has been used for many years as a source of uranium compounds in coloring glass and porcelain, and to a

[1] The pitchblende of Cornwall is mentioned in various articles in the *Transactions* of the Royal Geological Society of Cornwall, the Annual Reports and the *Journal* of the Royal Institute of Cornwall, the Reports of the Royal Cornwall Polytechnic Society, the *Transactions* of the Geological Society of London, the Memoirs of the Geological Survey of Great Britain, and in many other publications on the geology and mining of the region; but the references to it are usually very brief and often simply incidental to the discussion of some other subject.

small extent in photography, in reagents for chemical analysis, in mordants in dyeing and for other small purposes; but though of considerable market value for these uses, it did not become of very great importance until after the discovery of radium. The chief value of the ore is now in the radium it contains, but after the extraction of this, the remaining uranium has a value for the other uses mentioned.

NATURE AND MODE OF OCCURRENCE OF PITCHBLENDE.

The terms pitchblende and uraninite are often used synonymously to designate the same mineral, but more properly the term uraninite is a general name for all forms of the mineral and especially for the purer and distinctly crystalline variety, while the term pitchblende applies to the impure amorphous form. The two forms often occur together, but the latter is by far the more abundant. The term pitchblende arose from a certain pitchlike lustre which the mineral often displays, and was its original name in the old days before the discovery of uranium. At that time the mineral was vaguely supposed to be an ore of zinc, copper, iron or other metals. In 1789 Klaproth discovered a new metal in it, which he called uranium, and Haidinger[2] named the mineral uranin. J. D. Dana[3] later gave it the name uraninite, though in some earlier editions of his "System of Mineralogy" he used the term pitchblende. The amorphous form of the mineral is the one chiefly found in Cornwall, and as this paper treats particularly of that region, and as the name pitchblende has been established there by traditional custom, and appears throughout the literature of the region, the same name is used here. In an article on the mineral in general, the term uraninite would be better usage. In addition to the forms of the mineral included as uraninite or pitchblende, numerous other rarer varieties, differing somewhat in composition, have been described under the names of cleveite, bröggerite, and nivenite

[2] Wilhelm Haidinger, "Handbuch der bestimmenden Mineralogie," 1845, p. 549.

[3] "A System of Mineralogy," 1869, pp. 154–155.

The mineral when crystalline belongs to the isometric system and when amorphous is in a massive form often with botryoidal surfaces and a conchoidal fracture. It is black or grayish-black in color, opaque and often has a submetallic, glossy or a pitch-like luster. It has a hardness of about 5.5 and a specific gravity of 9 or over when pure, but both these qualities vary when the mineral is impure. It is often remarkably lacking in distinctive characteristics, so that its presence in small quantities is frequently overlooked.

The mineral is very complex and somewhat uncertain in composition. It consists mostly of the uranium oxides UO_2 and UO_3, in which the UO_2 seems to act as a base and the UO_3 as an acid, forming a uranate of uranyl, or a proto-peroxide of uranium. The relative amounts of the two oxides, however, vary greatly in different specimens, and no definite formula can at present be given.[4] With these oxides are usually other bases including lead, thorium, zirconium, lanthanum, yttrium, cerium, nitrogen, helium, argon, etc. These materials are in small amounts and varying proportions; some of them may be essential constituents of the mineral and others may not. With them are also other more common bases which may be impurities, but which are often difficult to distinguish from the essential constituents, among them being iron, calcium, and other substances. A noticeable amount of water, which may possibly sometimes be in chemical combination, occurs in some forms of the mineral.

A marked distinction between the different forms of the mineral is that the crystalline uraninite and the allied cleveite, bröggerite and nivenite almost always contain a notable number of the rare earth elements mentioned above, while pitchblende usually contains few or none of them. This may possibly be due to some form of alteration in the pitchblende, or perhaps to the fact that the other minerals mentioned are usually original constituents of igneous rocks, while pitchblende usually occurs in vein formations, a condition which it may have reached by the

[4] The commercial analyses of the mineral to determine its value as an ore are usually stated in terms of $UO_2 \cdot 2UO_3$, briefly expressed as U_3O_8; but this is simply an arbitrary assumption used to determine its market value.

solution and redeposition of the uranium contents of the other minerals, while the rarer elements may have been left behind or deposited elsewhere.

A rare element, however, which is common to all forms of this remarkable mineral, whether in the form of crystalline uraninite, cleveite, bröggerite, nivenite or the common amorphous pitchblende, is radium. This element is a product of, and in nature always accompanies uranium, whether that material is in the form of the minerals in question or of any of the many other uranium minerals found in nature; and among the still rarer accompaniments of uranium minerals are polonium, actinium and other new elements, the discovery of which has followed in the wake of that of radium. The amount of radium present in these minerals is, however, very small, and even in the purest forms of uraninite or pitchblende it is only between three and four grains per ton, and in the ordinary impure commercial forms, only a small fraction of a grain per ton, corresponding to a few centigrams or less.

Neither uraninite nor pitchblende have been found in large bodies in any one place. The crystalline uraninite occurs usually disseminated through certain igneous rocks, and pitchblende usually occurs as a subordinate mineral in veins of other ores, especially those of copper, silver and gold.

DISTRIBUTION OF PITCHBLENDE.

Radium was discovered in 1898 by M. and Mme. Curie in pitchblende from Joachimsthal, Bohemia, Austria, and the ores of that district soon became of great importance. Pitchblende, however, was known in many other places, and as soon as its value as a source of radium became known, they were carefully investigated. Among these localities were Przibram and elsewhere in Austria; several localities in Hungary; Schneeberg, Johanngeorgenstadt, Annaberg, and elsewhere in Germany; St. Just, St. Ives, Grampound Road, St. Austell, and many other places to be mentioned later, in Cornwall, England; and at several mines near Central City, Gilpin County, Colorado. Other

uranium minerals, such as autunite, torbernite, gummite, and various other forms, were known in most of these localities, but were generally in small quantities. In some places, however, these other minerals were found in sufficient quantities to encourage exploitation as a source of radium, as near Autun, France; Sabugal and Guarda, Portugal; near Mt. Painter, South Australia, and in other places. Finally, the carnotite of western Colorado and eastern Utah suddenly came into importance as an ore of radium and is now the world's chief source of it. Carnotite has also been found and exploited at Radium Hill, near Cutana Railroad Station, in South Australia.

Of all the pitchblende localities mentioned, Joachimsthal, Cornwall and Central City, are the only ones that have become of any considerable importance as commercial sources of radium, though other mines in Austria and Germany have for many years past regularly produced small quantities of pitchblende which were used for other purposes in the arts. Many of the mines that were exploited for pitchblende in the excitement following the discovery of radium, have since been closed as unprofitable, but this mineral is by no means a negligible source of radium, and there is always the possibility that it may somewhere be found in much larger quantities than at present known.

GROWTH OF KNOWLEDGE CONCERNING PITCHBLENDE IN CORNWALL.

In the early part of the nineteenth century uranium minerals were but little known in Cornwall, and William Phillips,[5] writing in 1815, stated that until within a few years the only locality known to have yielded "the oxyd of uranium" was the "Carharack" mine, south of "St. Die." He then described several other localities where he had found uranium minerals, which he referred to as "oxyd of uranium," though many of them seem to have been autunite or torbernite.

[5] William Phillips, "On the Oxyd of Uranium, the Production of Cornwall, together with a Description and Series of its Crystalline Forms," *Trans. Geol. Soc.*, London, Vol. III., 1816, pp. 112–120.

Somewhat later the nature of uranium minerals became better understood, but even in 1843, W. J. Henwood[6] reported that pitchblende

"occurs in great abundance among the copper ores of Weal Trenwith, and was long carefully collected, and thought to be black copper ore. The low prices obtained for the ores with which it was mixed, and the inferiority of the metal they yielded, equally disappointed the miner and the copper smelter; .... The ores were then inspected, and pitchblende being discovered among them, its nature and prejudice to the copper ores were explained to the workmen, by whom it has been, of course, since rejected."

Before long, however, uranium began to have a value in the arts, and in 1871 Richard Pearce,[7] in a letter from Swansea, England, describing a specimen of pitchblende which he had collected in Gilpin County, Colorado, said:

"It is the first time, I believe, that the mineral has been found in America."

Continuing he said:

"I found about 2 cwt., which had been thrown away on the refuse heap, and the person in charge of the property told me that it caused them a great deal of inconvenience, as it had come into the lode and cut the copper out. You may imagine his surprise when I told him it was worth in England about £400 per ton!"

In the early days of copper mining in Cornwall, however, pitchblende not only had no market value, but an extra smelting charge was imposed on ores containing any considerable quantity of it because of its deleterious effects. The miner, therefore, avoided it as much as possible, and left it untouched in the mine, or sorted it from the ore and threw it on the waste-dump. Later, however, when the use of uranium compounds in the arts gave it a market value, it was saved, and many of the old waste-dumps were sorted for it; while about the year 1889 a vein in

[6] W. J. Henwood, "On the Metalliferous Deposits of Cornwall and Devon," *Trans. Roy. Geol. Soc. Cornwall*, Vol. V., 1843, p. 19.

[7] Richard Pearce, "Memorandum on Pitchblende in Colorado," *Trans. Roy. Geol. Soc. Cornwall*, Vol. IX., Pt. I., 1875, p. 102.

the South Terras mine, which was unusually rich in pitchblende, was worked especially for that mineral. When still later pitchblende became important as a source of radium, much more attention was paid to saving it. Many of the old waste-dumps were again sorted for it on account of its greatly increased value, and several of the old copper mines which were known to have contained unusual quantities of pitchblende in the early days, were reopened, and the pitchblende that had once been carefully avoided was now just as carefully sought.

MODE OF OCCURRENCE OF PITCHBLENDE IN CORNWALL.

The pitchblende of Cornwall occurs mostly as one of the minerals of the copper deposits, though it occurs also with the tin deposits and in still other associations. With it are generally associated in addition to the copper, iron and other commoner materials, the rarer minerals of the region, such as native bismuth, nickel and cobalt minerals, sometimes lead and silver minerals, arsenic in the form of mispickel, and fluorspar. In some localities, however, the pitchblende occurs without these rarer accompaniments. With it also are sometimes associated various other uranium minerals, such as autunite, torbernite, zippeite, uraconite (uranochre), and other compounds, probably the products of the alteration of pitchblende. In fact, all the ores near the surface are more or less altered and the pitchblende is apt to be coated with, or even entirely replaced by, alteration products; but below, the unaltered black pitchblende appears, associated with sulphides and other unaltered minerals.

The most active days of copper mining in Cornwall have long since passed, and many of the larger mines have been exhausted, so that it is now often difficult to see just how the pitchblende occurred; but much information can be gotten from the old workings and the waste materials on the dumps and elsewhere. It rarely occurs in well-defined bodies, though J. H. Collins[8] describes a "leader" of it which had been traced for several

[8] J. H. Collins, "Observations on the West of England Mining Region," 1912, pp. 242–243.

hundred feet, and Richard Pearce[9] describes it as occurring commonly in small veins intersecting the main veins. In other cases it occurs as an impregnation throughout the copper ore and in the walls of the vein. Sometimes it forms thin lenses or incrustations on the walls, ranging from a mere film to a fraction of an inch, and in rarer cases to several inches, in thickness. In whatever form it occurs it is of very uncertain and sporadic distribution, and is rarely continuous for any considerable distances.

Pitchblende and other uranium minerals are very generally found in most of the copper mining districts of Cornwall, but are more abundant in some mines than in others. They occur in notable quantities at the Trenwith and the Providence mines in the St. Ives district and at the South Terras and other mines near Grampound Road, as well as at the St. Austell Consols mine, and other mines near St. Austell. They also occur in mines of the St. Just district, in the Dolcoath and other mines near Camborne, in mines near Redruth, Gwennap, Illogan, St. Blazey, Liskeard, at the Gunnislake mine near Callington, and in fact, in many other localities throughout Cornwall. In most of these places they are only in small quantities and are simply mineralogical curiosities; but in others they occur in important quantities.

THE TRENWITH MINE, CORNWALL.

A few years ago The British Radium Corporation began work at the old Trenwith mine, about two miles from St. Ives, with the object of mining pitchblende and extracting radium from it. The Trenwith mine was formerly worked for copper and to some small extent for tin; and it had always been noted for the quantity of pitchblende that it contained. At this locality the granite dips under the slates at a low angle of about 30°, and the country is intersected by greenstone dikes. The mine is on a vein which strikes easterly and westerly and dips almost vertically, with a slight inclination to the north. The upper workings are in the slates and the lower workings in the granite; and,

[9] Richard Pearce, "Note on Pitchblende in Cornwall," *Trans. Roy. Geol. Soc. Cornwall*, Vol. IX., Pt. I., 1875, pp. 103–104.

as common in Cornwall, the part of the vein in the slates carries copper ores, and the part in the granite carries tin ores. The mine was worked profitably in former days for copper, but when the workings extended into the granite the tin did not prove profitable, and the mine had been closed for many years at the time The British Radium Corporation took possession.

The pitchblende occurs especially on the walls of the vein, where it was left by the former copper miners, in the "horses" of rock within the vein, in the old waste-dumps and in the waste material used years ago to fill the old workings. The quantity of pitchblende in the parts of the mine containing tin ores is as yet problematical, as the latter have not been much worked; but the writer was shown by one of the directors of the Company a piece of feldspathic rock containing pitchblende from the tin-bearing part of the vein, so that the mineral seems to occur, at least to some extent, in the granite.

The pitchblende ore from the Trenwith mine consists mostly of a mixture of pitchblende, iron and copper minerals, and various gangue materials. It contains from a fraction of one per cent. of uranium oxides, commercially expressed in terms of U_3O_8, to 40 or more per cent., but the average produced is from 2 to 3 per cent., though higher grades of from 10 to 18 per cent. can be produced for special purposes. The British Radium Corporation extracts the radium from the pitchblende in the form of bromide, and has paid dividends on the enterprise. Aside from the radium contents of the pitchblende, the uranium is also a source of profit.

THE SOUTH TERRAS MINE, CORNWALL.

The South Terras mine is near Grampound Road in the Parish of St. Stephens, and has produced copper, tin, hematite, magnetite, and other ores. Several veins occur on the property, and one of them, long known for the uranium minerals it contained, is called the Uranium Lode. It strikes approximately north and south and varies from two to four feet in width, containing uranium minerals in a seam from a mere film up to seven or

eight inches or even a foot or more in width.[10] In the upper part of the vein the uranium occurred mostly as autunite, torbernite and zippeite, with disseminated particles of pitchblende; but with depth the pitchblende increased in quantity and the other uranium minerals decreased, finally being completely replaced by pitchblende, thus suggesting that they had been originally derived from pitchblende by surface alteration. Collins[11] states that at a depth of 30 fathoms pitchblende only was found. The depth of such transition in different districts will doubtless be found to vary according to the topography, drainage and other surface conditions.

About 1889, when there was considerable demand for pitchblende as a source of uranium compounds, before radium was known, the Uranium Lode was actively worked and was said to be the only mine in Great Britain at that time operated for uranium ores alone.[12] About five hundred tons of ore were sold up to 1907 and some was still left in the dump.[13] Since that time production has continued intermittently. When the value of uranium ores as a source of radium became known, a French company, known as Société Industrielle de Radium, commenced operations at the mine with the plan of shipping the crude ore to their laboratory at Gif, near Paris, for treatment. Financial and other complications have hampered the activities of this company, though they are said to claim to have produced some radium.

Uranium minerals have been found in more than usual quantities at the Engloshellan mine north of the South Terras mine and at the New Crow Hill mine south of it.

[10] J. H. Collins, "Observations on the West of England Mining Region," 1912, pp. 242–244.

[11] J. H. Collins, "Observations on the West of England Mining Region," 1912, p. 243.

[12] J. A. Phillips and Henry Louis, "A Treatise on Ore Deposits," 1896, p. 220.

[13] J. H. Collins, "Observations on the West of England Mining Region," 1912, pp. 243–244.

THE ST. AUSTELL CONSOLS MINE, CORNWALL.

Uranium minerals were at one time quite abundant at the St. Austell Consols mine near St. Austell, where they occurred in a series of veins intersecting a tin-bearing and copper-bearing vein in a north and south direction.[14] The uranium ores are here associated with nickel and cobalt minerals. This and other mines in the St. Austell district are reported by the government geological survey to have produced about 576 tons of uranium ores in the years 1854 to 1863; 1873–1881; 1890–1906.[15]

OTHER MINES CONTAINING PITCHBLENDE IN CORNWALL.

Many other instances of deposits containing pitchblende in Cornwall might be described, but those mentioned above represent the different modes of occurrence and are among the localities where it has been most abundantly found.

[14] R. H. Williams, "Note on the Occurrence of Nickel and Cobalt at St. Austell Consols Mine," 39th Rept. Roy. Inst. Cornwall, Appendix VII., 1858, p. 32, cited in "The Geology of the Country around Bodmin and St. Austell," by W. A. E. Ussher, G. Barrow, and D. A. MacAlister, A. R. S. M., Memoirs of the Geological Survey, London, 1909, pp. 155–156.

[15] "The Geology of the Country around Bodmin and St. Austell," by W. A. E. Ussher, G. Barrow, and D. A. MacAlister, A. R. S. M.; Memoirs of the Geological Survey, London, 1909, p. 135.

ON THE OCCURRENCE OF SILVER IN ARGENTIFEROUS GALENA ORES.

ARVID E. NISSEN AND SAMUEL L. HOYT.[1]

The object of this investigation was to ascertain the manner of the occurrence of silver in argentiferous galena. Finlayson[2] states that he examined a considerable number of specimens of galena from deep workings but that in none of these could he identify any silver or silver bearing mineral. A question here suggests itself as to which silver mineral may be expected to occur in galena. The silver ore being primary, and the galena deposits being considered as precipitations of lead, silver, copper, and iron from hot ascending waters, the sulphide, argentite, is the mineral that would be most reasonably expected to occur. Friedrich[3] worked out part of the constitution diagram galena-argentite and found the compositions between 2 per cent. galena and 2 per cent. argentite to consist of heterogeneous mixtures of practically pure galena and argentite. He gives the melting point of PbS as 1114° C., Ag_2S as 835° C., and the eutectic composition at 77 per cent. Ag_2S at 630° C. An evolution of heat, which becomes very weak toward the galena end of the diagram, was recorded at 175° C. No eutectic structure was recorded under 5 per cent. Ag_2S. No limits of solid solution are given.

For the purpose of identifying argentite in the ores through comparison with a mineral known to be argentite, a series of synthetic melts containing definite amounts of galena and argentite was prepared from lead sulphide and silver sulphide. The lead sulphide used was Wisconsin galena, free from silver and other impurities, and galena concentrates. The latter had some

[1] Communication from the metallographic laboratory, Minnesota School of Mines.

[2] Finlayson, ECON. GEOL., Vol. 5, p. 727.

[3] Friedrich, "Metallurgie," Vol. 4, 479, 1907.

silicious impurities as well as small amounts of silver. The argentite was produced synthetically by boiling chemically pure silver foil of a known weight in flower sulphur for 20 minutes. Then 40 gm. of galena was poured in on top, without removing the excess sulphur. The crucible (a No. 0 graphite crucible) was covered with a tight fitting silica cover and placed in an air-gas furnace of the Méker type, which had been previously heated to about 1200° C. About 15 minutes were required for melting down the mixture, whereupon the hot crucible and melt were transferred rapidly, without pouring, to a silica crucible, previously heated, and a cover put on. In this manner the melts cooled to room temperature in about 40 minutes. The composition of these melts was obtained from the known weight of silver calculated to Ag_2S (87.06 Ag) and from the known weight of galena. Some of the melts were chill cast in order to note the effect on the texture of the galena.

During the fusion of the ores, the excess sulphur came off as heavy fumes of SO_2, but the atmosphere in the crucible was plainly reducing. Small dots of sulphur were discernible on the polished sections. These disappeared when the specimen was heated in a gas flame. After trying iodine, hydrochloric acid, picric acid and nitric acid, the latter was found to be the only etching reagent that could be successfully used to develop the structure. Cold concentrated acid was used for the natural ores and warm 50 per cent. acid for the melts. The acid attacked the galena, coloring it dark and leaving the argentite light.

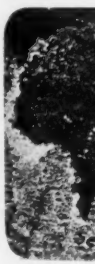
The results obtained from this investigation are listed below. This table gives the melts and their compositions, together with the numbers of the microphotographs illustrating the structure and appearance of galena and argentite.

TABLE I.

MELTS MADE OF LEAD AND SILVER SULPHIDES AND PLATES ILLUSTRATING THEM.

Melts.	Composition.	Illustration.
1.	PbS 99.38, Ag_2S .62	
2.	PbS 98.86, Ag_2S 1.14	Plate 7, Fig. 1
3.	PbS 98.30, Ag_2S 1.70	Plate 7, Figs. 2 and 3
4.	PbS 97.21, Ag_2S 2.79	

PLATE VII.



EXPLANATION TO PLATE VII.

FIG. 1 x 78. Remelted galena containing 1.14 per cent. Ag_2S, 98.86 per cent. PbS.

FIG. 2 x 78. Remelted galena containing 1.70 per cent. Ag_2S, 98.30 per cent. PbS.

FIG. 3 x 580. Remelted galena containing 1.70 per cent. Ag_2S, 98.30 per cent. PbS.

FIG. 4 x 78. Ore from Eureka Nevada. Shows galena replaced by mineral, also by secondary and possibly primary argentite. 0.78 per cent. Ag_2S.

FIG. 5 x 78. Same as Fig. 4.

FIG. 6 x 78. Ore from Mendota Mine, Georgetown, Colorado. 0.367 per cent. Ag_2S.

FIG. 1.

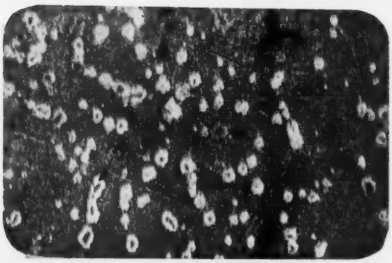


FIG. 2.

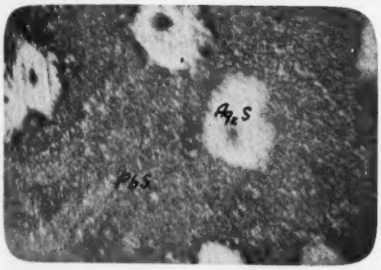


FIG. 3.

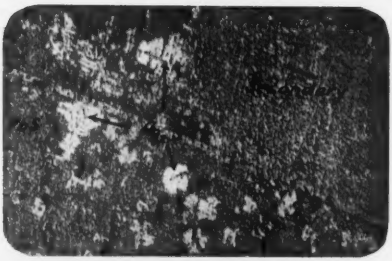


FIG. 4.

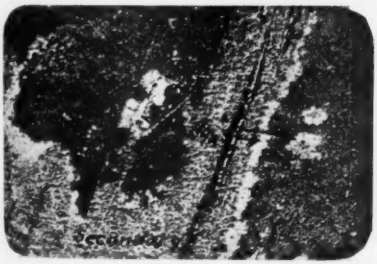


FIG. 5.

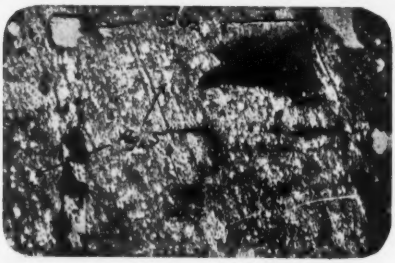


FIG. 6.

The argentite is the white constituent and appears as a circular or irregular mass and generally has a hollow center. Argentite may be easily distinguished from the other white sulphides and from galena, by determining the relative hardness with a fine cambric needle. Evidence of a eutectic for these compositions was not found. The argentite may be coated dark on long deep etching, in which case it is necessary to repolish slightly on a chamois skin before it can again be readily differentiated. However, the latter operation is not very satisfactory, a better way being to repolish on the rouge wheel and then re-etch to the proper depth. The dark areas in the photographs are pits. The galena, which is silvery and brightly metallic before etching, takes on a dark gray or brown film, which, if the etch is light, can readily be removed by polishing on a chamois skin.

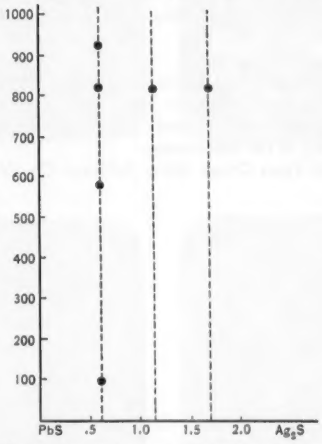


FIG. 28. Showing melts that were annealed and quenched at various temperatures.

From the argentite segregations it would seem that the limit of solid solution at ordinary temperatures is inside of 0.6 per cent. Later, in the discussion of the natural ores, it is shown

PLATE VIII.

EXPLANATION TO PLATE VIII.

FIG. 7 x 1000. Ore from Ten Mile District, Montana. 0.253 per cent. Ag_2S.

FIG. 8 x 140. Ore from Comet Mine, Jefferson Co., Mo. 0.195 per cent. Ag_2S.

FIG. 9 x 1000. Same as Fig. 8.

FIG. 10 x 78. Ore from Idaho Springs, Colorado. Shows as probable secondary occurrence of Ag_2S. 0.12 per cent. Ag_2S.

FIG. 11 x 130. Galena concentrate melt. Shows the eutectic structure. The gangue is an impurity in the concentrate.

FIG. 12 x 140. Ore from Comet Mine, Jefferson Co., Montana. 0.195 per cent. Ag_2S.

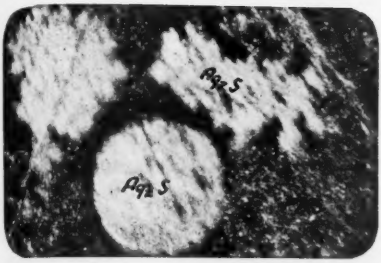


FIG. 7.

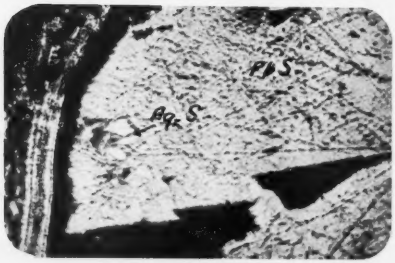


FIG. 8.

FIG. 9.

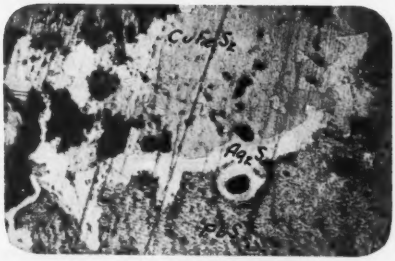


FIG. 10.

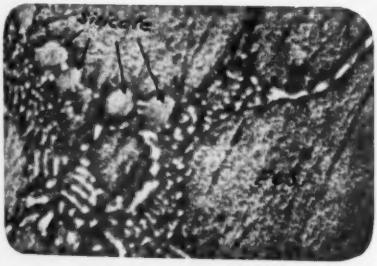


FIG. 11.

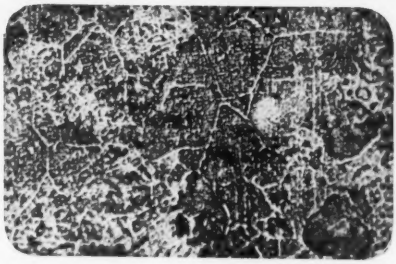


FIG. 12.

that this is probably inside 0.2 per cent. Ag_2S. To ascertain the limits of solid solution and the structure of the argentite at higher temperatures, melts 1, 2 and 3 were annealed and quenched from temperatures as indicated in Fig. 28.

In no case was there any evidence of the argentite going into solution. All specimens quenched from above 800° C. showed evidence of having been in the partly liquid zone. In no case did the melt take any appreciable amount of impurity from the graphite crucible. The quenched galena was, as a whole, coarsely crystalline but contained small areas of a finer texture. The argentite showed a prevailing ring or doughnut structure, which was in many cases elongated as in the slowly cooled specimens. Plate VIII., Fig. 11 shows, by way of comparison, the eutectic structure of a slowly cooled remelted galena concentrate. The round gray mineral in the eutectic is a silicate impurity in the concentrate.

No final conclusions as to the constitution of these concentrations can as yet be drawn. A thermal analysis of the argentite-rich concentrations would be of great interest in locating the limits of saturation, the range of solidification, etc. The exact bearing of the results of such an investigation on the constitution of argentiferous galena is still a matter of conjecture. From our results as established thus far, however, we are aware of no fundamental difference between the occurrence of argentite in the natural ores and in the synthetic melts.

The ores which were examined are tabulated in Table III.

TABLE III.

No.	Place.	Impurities.	Oz. Ag.	Per Cent. Ag_2S.
100	Inyo Co., California	Pyrite, sphalerite, gangue, chalcopyrite.	176.80	.60
101	Eureka Dist., Nev.	Pyrite, gangue.	200.40	.78
102	Mendota Mine, Georgetown, Colorado.	Sphalerite, quartz pyrite.	95.20	.367
103	Comet Mine, Jefferson Co., Montana.	Pyrite, gangue.	51.80	.195
104	Clear Creek, Colo.	Pyrite, quartz.	22.40	.08
105	Ten Mile District, Montana.	Quartz, sphalerite, pyrite.	63.94	.253
106	Cuevas Alemria, Spain.	Pyrite, gangue.	101.04	.392
107	Idaho Springs, Colo.	Sphalerite, quartz, pyrite.	31.72	.12

The compositions were obtained by fire assay for silver, and converting into Ag_2S.

Plates VII. and VIII., Figs. 4, 5, 6, 7, 8, 9 and 10, illustrate the occurrence of argentite in native ores. In Figs. 4 and 5 the argentite is shown occurring in and near the fissures in the ore and is therefore believed to be secondary, the galena having been replaced by a secondary mineral. This replacement or oxidation appears to have been preceded by an extensive shattering of the ore. The argentite occurs at the contact of the alteration and in the fissures and has evidently been introduced at a later period. Some argentite also occurs in the galena away from fissures and may be primary. However, a section at 90° to the one shown might disclose that the silver sulphide was connected with a fissure. Fig. 7 shows argentite. Compared with the synthetic melts (Plate VII., Fig. 3) a similarity is readily noted. The rounded form of argentite is very characteristic of all the melts, although the irregular structure is not at all uncommon. Fig. 6, Plate VII., shows the occurrence of argentite in a medium-grade ore. The photograph does not give a true idea of the average silver content of this ore as it represents a segregated area. The dark areas showing the cubic cleavage of galena, are pits, gouged out during polishing. Fig. 8 shows a small group of argentite masses in a coarsely crystalline galena. The same under higher magnification, is seen in Fig. 9. No euhedral crystals or argentite are found in any of these ores. The pyrite on the left shows cubic crystallization. A pit is noted in the center of one of the argentite masses, which corresponds to the structure of the melts. Fig. 10 illustrates a probable secondary or later occurrence of argentite. This also represents a segregation of argentite. The galena and sphalerite are here apparently of contemporaneous origin. They have been shattered and a solution carrying Cu, Fe and Ag has entered, depositing argentite and chalcopyrite. The occurrence of argentite in the chalcopyrite and the sharp boundaries are noteworthy as is the doughnut structure of the argentite in the galena. No argentite was found in the examination of the sections of ore, No. 104, although the assays show silver. As ore No. 104 contains only 22.4 oz. per ton (.08

per cent. Ag_2S) of silver, it may be inferred that Ag_2S and PbS are here in solid solution. A polygonal structure of galena was obtained from three of the ores (Fig. 12, Plate VIII.). The lenses did not allow sufficiently sharp definition to distinguish any intergranular filling. However, in one of the ores, the argentite, while not appearing as a continuous filling, outlines the galena very suggestively into polygonal areas, and the filling can be very plainly traced to the large argentite segregate in the center of the figure.

The conclusions from this investigation are:

1. That silver occurs as argentite in some primary and in some secondary argentiferous galena ores.

2. That the limit of solid solution at atmospheric temperatures is below 0.2 per cent. Ag_2S.

3. That the eutectic, as given by Friedrich, is not developed in concentrations below 2.70 per cent. Ag_2S.

In conclusion we wish to thank W. H. Emmons for his kind interest throughout the course of this investigation and G. P. Merrill of the Smithsonian Institution for his courtesy in supplying the material.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

ORIGIN OF CERTAIN ORE-DEPOSITS.

Sir:—The origin of bodies of certain kinds of ores in regions of practically level sedimentary rocks, which show little disturbance and where manifestations of underlying igneous activity are wanting at the surface, as illustrated in the Missouri mining regions, has been the subject of much controversy. Such ores, which are chiefly those of copper, lead, and zinc, are apt to be found, as is well known, especially in limestones, as more or less flattened lenticular masses, often of large size.

Concerning the mode of origin of these ore-bodies opinions are still widely divergent. Some have held that they have been directly deposited from sea-water through some unknown process, contemporaneously with the enclosing rocks. Others, observing the common association of ores with intrusions of igneous rocks in disturbed districts, and noting that the accompanying elements and minerals are similar to those found in such deposits of igneous origin, have ascribed their occurrence to igneous rock masses yet buried below.

Still another method of explanation is offered by those who, finding no direct evidence of igneous activity, point to the wide distribution of scattered ore-particles, especially of galena, in certain limestones, and believe that the ore-bodies have been formed by the lateral movement of liquids which have taken these particles into solution and concentrated them. A paper read before

the Geological Society of America at its recent meeting in Philadelphia by Professor Van Ingen tends to afford support for this view, in that it offers in some measure an explanation for the origin of these ore-particles disseminated through the strata. He points out the common occurrence of galena and other ores in fossils, the fact that barite crystals are often found in them, as in the nodular fossil masses of the Pierre shales, that fluorite is found in teeth, bones, etc., and correlates this with the fact that copper, often in considerable amount, is found, as announced by Mendel, in the soft bodies of bivalves, especially in oysters. The implication lies that the metals have been secreted from sea-water through the agency of organic life, as so well illustrated by the work of the iron bacteria.

On the other hand the chief difficulty in accepting this view, that the great ore-bodies have been formed by the concentration of scattered particles, still remains. For it is clear that where the ores are in the sulphide form this concentration must have been effected below the water level, out of reach of the oxidizing zone, and it is also evident that to accumulate such large masses very wide tracts of country must have had their thinly disseminated particles transported in solution to the central depot. The question then arises: what caused such a widespread convergence of laterally moving solutions; through what kind of passageways could they find their courses and why were the limestones not completely burrowed and honeycombed by them in such a general leaching action? That particular underground waterways are well-known in limestone regions is beyond doubt, but it has not yet been shown that such caves are especially noted for containing ore-deposits, as one might expect from such an explanation of the origin of these deposits. In addition, while one can understand from the chemical point of view how sulphides oxidizing above the ground-water level might be taken into solution and on passing down below that level and coming in contact with minerals of high sulphur content might react with them and be changed back into lower sulphides, it is difficult to see how the sulphides themselves could be taken into solution as such, carried long distances later-

ally, and then deposited without change in their chemical composition, as this explanation demands.

Moreover, the dissimilar properties of the ores in different districts, the variable relations between lead, zinc, and copper in closely related ones, the occurrence of nickel and cobalt, and in places of fluorite, which latter when occurring in large masses could scarcely represent an extract from the teeth and bones of animals, etc., still remain unexplained.

For these reasons it seems wise to re-examine the view that these deposits may have been formed by igneous activities; if the probability of this could be shown it would be the more satisfactory since they could then be correlated with the well-known class of occurrences connected with intrusions, and all would be brought under one general heading, while the peculiarities noted above and difficulty of explanation under the theory of lateral concentration would become understandable and easy of comprehension.

The chief difficulty which those who uphold the igneous origin of these ore-bodies have to meet is that, in the mid-Mississippi valley region, there are no external evidences of any such igneous action ever having taken place, at least not in the manner in which we are accustomed to think of its external manifestations, and therefore in the lack of such evidence there is in the minds of many no warrant in appealing to it as a factor in the case. Is this really a fact and is such a conclusion justified?

In referring to igneous activity we are accustomed to think of definite extrusions of lava which are material evidences visible to us, or of intrusions of magma which become visible when erosion has laid bare the igneous rock masses by the removal of their covers, and unless we see these things there is a tendency to assume that no volcanic action, using this term in its broader sense, has taken place. This view, in the opinion of the writer, is one entirely too narrow, for reasons to be now explained.

The underlying magmas of the earth must be considered as consisting of two different parts, one volatile, the other non-volatile. As is well known, the latter is for the most part a molten mass of metallic oxides with silica; the former, various elements and compounds which are ordinarily gaseous or become

so when heated. Our knowledge of the composition of the non-volatile portion has been obtained by chemical analyses of igneous rocks, of which many thousands have been made; information with respect to the volatile part has hitherto been imperfect, having been gained by observation of the gases occluded in the rocks, of those issuing from the earth in volcanic areas, or more indirectly by the compounds in the rocks which they have produced after leaving the magma. In these later days, however, attempts have been made to study them more directly as they depart from exposed molten magmas, and with remarkable success by Dr. Day and his colaborers of the Carnegie Geophysical Laboratory.

Under pressure in the depths below, these volatile substances are to be regarded as in solution in the magma; the latter itself indeed is to be considered as a mixed solution in which, due to the pressure, the gaseous constituents are held in liquid form, like carbon dioxide in a corked bottle of carbonated water. When the magma rises toward the surface, as in volcanoes, and the pressure is relieved the volatile constituents, as if the stopper had been removed from the bottle, assume the gaseous form and depart, often with terrific energy, as seen in great eruptions. In thinking of igneous activity, as said before, we are too apt to consider only the non-volatile part of the magma whose solid masses furnish such tangible evidence, and to disregard the volatile portion, except in those cases where its explosive energy forces our attention. It appears to the writer that this is a mistake. Igneous activity may consist of many phases. It may show itself at the surface or in the upper zone of the lithosphere by extrusions or intrusions of magma, as we ordinarily conceive them, in which case there are the igneous rock-bodies left as evidence. Or not rising to such heights in the lithosphere, where pressure has been relieved or changed by movements of the overlying masses, whether these be epeirogenic, or orogenic, or of general diastrophic nature, we should expect a departure to a greater or lesser degree of these volatile substances. Under some conditions these might make their way upward through the covering masses with violence, as appears to have been the case in the Eifel district of eastern Germany, in Italy, and elsewhere, which exhibit explosion craters with

little or no solid lava products. But a moment's reflection will show, however, that for one case where these upward-rising gases from underlying magma gather sufficient strength to erupt violently, there must be a vastly greater number where they are quietly working their way upward as opportunity affords, to either issue quietly into the air or to be absorbed by the meteoric waters circulating in the upper lithosphere.

As there is every degree between eruption with catastrophic violence to quiet outwelling of magma of mixed volatile and non-volatile substances under proper conditions, so there should be all gradations in the mode of rising of the gaseous portion through the shattered lithosphere and its escape at the surface.

Furthermore, as it is natural to believe that magma, perhaps in the pseudo-rigid but potentially liquid form conceived by Iddings,[1] must everywhere underly the outer rock zone, so everywhere there will be a tendency for it to rise upward when opportunity permits. One of the first effects of relief of pressure on its upper surfaces would be the liberation of the volatile constituents. It may well be that in many places no further action than this happens. All the shiftings and movements of the lithosphere would then tend, in variable degree, to be attended by upward movement of gaseous constituents, and in the same measure the passage of magma upward would be heralded by the development or increase of solfataric or fumarolic activity at the surface; a fact well known in volcanic regions. This quiet working upward of volatile matters may then be considered as the mildest phase of volcanic action with which we are acquainted and one which has happened, is happening, or will happen, practically everywhere over the world. To it we may ascribe in large measure peculiarities seen in the composition of many mineral springs and waters in otherwise apparently non-volcanic regions.

The application of this principle, the quiet upward movement of volatile magmatic material, if it be admitted, in explaining the origin of the ore-deposits previously mentioned, is evident. If sulphide ores have been deposited from acid emanations in those cases where the connection with intruded bodies of magma is clear

[1] "The Problem of Volcanism," p. 164, 1914.

and unmistakable from the visible presence of the latter, it seems a natural and inevitable step to ascribe those instances where no igneous rocks are seen or known in connection with them to such emanations working upward from magma in the depths below. It does not appear necessary to establish the connection that magma should have ever reached the surface or, perhaps, even the upper zone of intrusion in the lithosphere, though naturally where this has happened the chances for ore deposition would be greatly increased.

From this it would follow that we cannot definitely say that there is any region of the earth which may be regarded as one in which it is useless to look for metalliferous deposits. Areas of little or undisturbed strata may, as we have seen, contain them. If the emanations are acid, the deposits will naturally be most apt to occur in limestones, and the older the strata are, the more likely it is that such action may have affected them. If igneous activity of a more pronounced character has displayed itself at some time in their neighborhood the chances for such deposits are obviously still greater.

As to the mid-Mississippi area which has served as a basis for this suggestion, it can be said that evidences of the milder modes of igneous activity, in addition to the occurrence of the ores themselves, are not wanting in many places, while in some it has assumed a more active and evident form. Thus in central Arkansas are many intrusions of syenites and related alkalic rocks of late Cretaceous age; there are also the occurrences of diabase, porphyries, etc., in the eastern Ozarkian uplift of Missouri; of peridotite dikes in Kentucky and Illinois, with which are associated ores and fluorspar, the latter in huge masses, and indicative of fumarolic action from magma below. The great volumes of "sulphurous" gases, which issued from the ground and whose presence is mentioned by so many observers at the time of the New Madrid earthquakes in 1811–12, may possibly have had such an origin, and afford an example of the outbreak of magmatic vapors from below. It is not suggested that they were the cause of the seismic phenomena, but merely attendant upon it; the disturbance and displacements of the rock masses giving them an opportunity to

escape. All of these instances and others that might be cited appear to point in the same general direction.

It has not been the object of this paper to attempt a general discussion of the origin of the ores of particular districts or of the literature which has been written concerning them, but merely to offer from the petrologic side a suggestion for the consideration of those who are interested in the genesis of ores in such situations.

L. V. PIRSSON.

SHEFFIELD SCIENTIFIC SCHOOL OF YALE UNIVERSITY,
NEW HAVEN, CONN., Jan., 1915.

A CAVE DEPOSIT.

Late in the fall of 1904 while making an examination in the vicinity of Battle Mountain, my attention was called to a cave which had just been opened by a prospector. A rather hurried visit and inspection was the result. The time allowed only a few samples and specimens to be taken and a limited number of observations to be made. It was my intention to make a chemical examination of the material, and if the results were significant to return for a thorough examination. The examination of the material was partially made and so interesting were the results that further chemical studies were postponed until the detailed examination of the cave could be made and systematic sampling done. Several years slipped by; other investigations demanded immediate attention, and soon the incident became a dim memory. Some days ago in discussing the occurrence of certain minerals with W. H. Emmons I recalled the incident of the cave and described it to him. The analyses made at the time were discussed and he expressed the opinion that they were of sufficient interest to present to the readers of ECONOMIC GEOLOGY. The facts which follow are presented as an incomplete study of certain well-known chemical reactions which are brought about by the decomposition of pyrite by meteoric waters.

The mining claims upon which the cave was found are about 12 miles southeast of Battle Mountain, Nevada, and close to what was then known as Wilson's ranch. Several thick lenses of

massive pyrite had been discovered by the prospector and opened up by surface cuts and short drifts. The material removed consisted largely of limonite in which were kernels and masses of undecomposed pyrite. The usual open or porous structure was conspicuous. A ravine which ran transversely to the strike of the lenses permitted of the driving of a drift at some considerable depth below the older workings. This drift had been extended but a short distance when it penetrated a natural cave. The cave was about 100 feet in length and of irregular width and height. The maximum width was about 50 feet and the range of vertical height about the same. The prospector informed me that when the cave was first opened a rush of gas drove him out of the drift. A cross section of the cave showing the relation to the deposit is given.

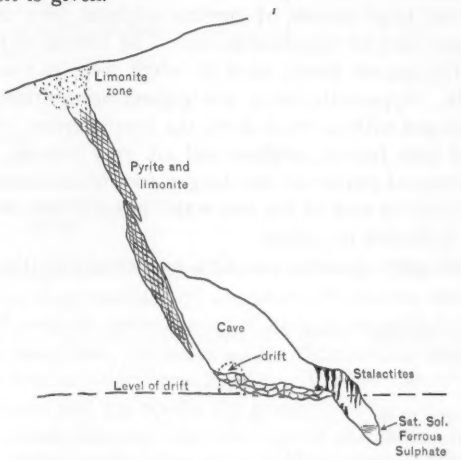


FIG. 29. Cross section of cave showing relation to deposit.

The drift connecting with the cave had intersected several fissures in which limonite in stalactitic form and in botryoidal masses had been deposited. The floor of the cave was covered with large blocks of rock which had fallen from the roof. Above the drift level there was nothing of particular interest.

Below the drift level a portion of the cave opened out and sloped steeply downward, terminating in a more or less level portion, at one end of which was a deep hole filled with a saturated solution of ferrous sulphate. From the roof of the cave stalactites hung down and joined with the stalagmites from the floor. Both were brown and were roughened in an unusual manner. They appeared to be made of an aggregate of coarse crystals. Broken they showed a coarse concentric structure. Upon the surfaces of the rock masses were coarse brown crystals. These crystals practically covered the rocks in the lower part of the cave. Upon the floor and between the rock masses was a soft ash gray deposit. This occurred in small heaps and powdery masses in which the foot sunk. Some portions were kaolinitic in character. In removing this loose material in the lower part of the cave large masses of ferrous sulphate were unearthed. The masses were of considerable size. The ferrous sulphate was in clear transparent pieces, some of which were as much as one could lift. Apparently there was present several tons of this compound and without much doubt the lower portion of the cave was filled with ferrous sulphate and ash gray powder. I broke out a number of pieces two feet long, a foot wide and half a foot thick. From the roof of the cave water in small amount dropped down at a number of points.

The ash gray powder was first examined and the analysis follows:

	Per Cent.
Water insoluble residue (not examined)	17.59
Sulphur	5.12
Soluble in Water	
Ferrous oxide	15.46
Ferric oxide	1.51
Alumina	1.65
Lime	trace
Sulphuric anhydride	21.90
Cupric oxide	.13
Water of crystallization (calc.)	20.08
Hygroscopic moisture	12.38
Unaccounted for	4.18

(Part of the sulphur was determined by dissolving with carbon

bisulphide and the remainder by difference method. The amount removed by carbon bisulphide was equivalent to 2.84 per cent.)

It is probable that much of the unaccounted portion was sulphur. The material was moist and gave an acid reaction with litmus. The compounds present were ferrous sulphate, ferric sulphate, aluminum sulphate, copper sulphate and sulphur. The nature of the insoluble residue was not determined.

The brown crystals composing the stalactites, stalagmites and covering the surface of the rocks gave the following analysis:

Residue (insoluble in HCl)	0.00
Ferric oxide	24.55
Alumina	2.21
Lime	20.41
Sulphuric anhydride	31.78
Loss at 110° C.	16.00
Loss at 110° C. ignition	6.37
Total	101.52

Recalculating this analysis:

Gypsum	61.23
Limonite	28.67
Alumina	2.21
Excess sulphuric anhydride	2.64
Loss ignition	6.57

The crystals had the appearance of being a distinct mineral. Apparently they consisted of a mixture of limonite and gypsum.

As the original pyrite contained little or no gold or silver the examination of the cave material for these metals would be unlikely to give any significant results. However, several portions were assayed and the results are given.

Gray friable material from the floor of the cave:

Soluble portion showed no gold or silver.

Undivided material showed no gold or silver.

Large gypsum and iron crystals from floor of cave:

No gold or silver.

Iron and gypsum deposit from near bottom of cave:

Silver 0.3 oz. per ton (0.001 per cent.).

Gold trace.

Limonite nodule from drift:

Traces of silver and gold.

Gypsum and iron stalactite:

No gold or silver.

White, clay like material from lower part of cave:

Silver 6.7 oz. per ton (0.022 per cent.).

Gold trace.

Ash gray material from lowest part of cave:

Silver 1.86 oz. per ton (0.006 per cent.).

Gold 0.18 oz. per ton.

In the absence of further details these results do not admit of any significant discussion.

The occurrence as a whole, while it does not add materially to what we already know about the decomposition of pyrite, is exceptional in that practically all the products of the reactions have been retained in the lower part of the cave. The absence of any drainage channel prevented the removal of the soluble products. Sufficient evaporation took place to result in the concentration of solutions and the crystallization of the soluble compounds. The absence of carbonates and the presence of gypsum indicate the action of free sulphuric acid. The reaction of this acid upon calcium carbonate contained in the wall rocks produced the gypsum and also the carbon dioxide which must have filled the cave and prevented entrance when the cave was first broken into. The small amount of seepage water was just sufficient to dissolve and carry the products to the bottom of the cave.

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REVIEWS

Gesteine für Architektur und Skulptur. By O. HERRMAN. xii + 119 pp. Gebrüder Borntraeger, W. 35 Schöneberger Ufer 12a, Berlin, 1914.

This book is the second edition, revised and enlarged, of the appendix to the author's work, "Steinbruchindustrie und Steinbruchgeologie." Its purpose is to give condensed information to those engaged in different branches of the stone industry and related occupations. Thus stone workers and architects will find it a convenient book of reference for fundamental petrologic data and the geologist may turn to it for a summary of the important technologc features of the stone industry; furthermore, all engaged in the use, examination, or study of building and ornamental stone will find in it a convenient descriptive catalogue of the more important European, and a few of the best known American stones. The introductory pages include a bibliography of technical journals and of other, comparatively recent, literature, with directories of European stone-testing laboratories and of granite, serpentine, and marble works.

The main part begins with six pages devoted to the following general information: definition and scope of the term rock, factors determining the degree of hardness of rocks, coarseness and fineness of grain, adaptability for building and ornamental uses under different conditions, and a historical review of the use of hard and soft stones in sculpture. The remainder of the book is essentially a descriptive catalogue divided into three sections: igneous rocks, metamorphic rocks and sedimentary rocks. Marbles are included with limestones under sedimentary rocks, a desirable arrangement from an economic standpoint. Each section begins with a brief explanation of the modes of origin and textures, of the group of rocks under consideration, and is subdivided according to the rock types (for example, granite, diorite, porphyrite, basaltic rocks, etc.). Each subdivision is introduced by a brief description of the typical characters and principal varieties of the rock type, and consists mainly of summarized descriptions of the more important stones of different countries. These descriptions give name and location, distinguishing characters, a few names of buildings or monuments built of the stone, and names of companies furnishing it.

The book should prove very convenient to any one wishing brief gen-

eral information on European building stone. The selection of American stones, however, will hardly meet with unqualified approval from American stone producers. Among the granites only those from Barre, Bethel and Hardwick, Vermont, Stony Creek, Connecticut, and Montello, Wisconsin, are given condensed descriptions, while other well known eastern granites are merely listed in fine print, and the extensively used granite from Milford, Massachusetts, is not even mentioned. Those listed, however, serve to represent the variety in color and texture of American granites. Wisconsin is the only one of the central and western granite-producing states mentioned. The only American marbles described are the well known Vermont and Georgia marbles and the Mexican onyx marble. The only limestone mentioned is that from Bedford, Indiana, and the sandstones are represented by the Potsdam, Medina, and the Hudson River bluestone of New York, and the Portland brown stone of Connecticut. No mention is made of the famous light-gray and buff sandstones of northern Ohio.

G. F. LOUGHLIN.

SCIENTIFIC NOTES AND NEWS[1]

PROFESSOR JAMES F. KEMP, of Columbia University, has been examining a mining property in Butte. On his return he delivered the address to the graduating class of the Michigan College of Mines on April 16.

MR. H. G. FERGUSON, of the U. S. Geological Survey, has just returned from a trip to South America, where he has been examining mines.

N. B. DAVIS, assistant in economic geology at Cornell University, has been appointed clay technologist in the Canadian Bureau of Mines.

B. B. THAYER is in Montana on an inspection tour.

MR. A. A. HASSAN is examining manganese deposits of Tennessee, West Virginia and Virginia.

MR. WARREN S. SMITH lectured April 5 at the American Museum of Natural History in New York on the areal and economic geology of Skykomish Basin, Wash.

POPE YEATMAN will remain in Chile until about the end of May, when it is expected that operations will be going on regularly at Chuquicamata. He is expected to return to New York about the end of June.

THE EMMONS MEMORIAL FELLOWSHIP has been awarded to Mr. Max Roesler, of Columbia University.

THE WEST VIRGINIA GEOLOGICAL SURVEY has just issued a report on Logan and Mingo counties. In addition to the detailed

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

description and revision of coal beds and other geologic formations exposed in these counties, the geologic map gives the structure contours and outcrops of the no. 2 gas coal, as also that of several other valuable coal beds, along with many new sections, analyses, etc.

THE INTERNATIONAL ENGINEERING CONGRESS will be held September 20 to 25 in San Francisco. Arrangements have been made for a special train leaving New York, Thursday, September 9, for the convenience of the members of the civil, mining, mechanical, electrical and marine engineering societies.

FREDERIC KEFFER has resigned as consulting engineer and geologist of the British Columbia Copper Co. and will open offices in Spokane, Wash., as consulting engineer with Henry Johns, mine superintendent for the same company.

THE GEOLOGISTS of the University of Texas, including the staffs of the school of geology and the bureau of economic geology, have organized the Texas Geological Club for the purpose of stimulating interest in geological matters and geologic research.

A. CHESTER BEATTY has taken up his residence in England on account of his extensive interest in British companies developing and operating mines in Siberia and India. His London office is at 1 London Wall Buildings.

BAIRD HALBERSTADT, long assistant geologist of Pennsylvania, gave a reception at Pottsville, Pa., April 21, to celebrate the conclusion of one third of a century in geological work.